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УДК 621.313.3:62-83

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ENERGY EFFICIENCY OF PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVES: DESIGN, CONTROL, AND DEVELOPMENT TRENDS

The work examines the factors that determine the energy efficiency of electric drives based on permanent magnet synchronous motors (PMSMs). It considers the design features of PMSMs, the sources of losses and the approaches to their modelling, as well as modern control strategies, including efficiency-oriented and sensorless control. Special attention is given to the IEC efficiency classes and the energy-saving potential of high-efficiency motors. The study concludes that the greatest gains are achieved when the motor, the power converter, and the control algorithm are designed and optimised as a single electromechanical system.

Keywords: *permanent magnet synchronous motor, electromechanical energy conversion, energy efficiency, electric drive, field-oriented control, sensorless control, efficiency classes.*

У роботі розглянуто чинники, що визначають енергоефективність електроприводів на основі синхронних двигунів з постійними магнітами (СДПМ). Проаналізовано конструктивні особливості СДПМ, джерела втрат та підходи до їх моделювання, а також сучасні стратегії керування, зокрема енергоефективне та безсенсорне керування. Особливу увагу приділено класам енергоефективності IEC і потенціалу енергозбереження високоефективних двигунів. Зроблено висновок, що найбільший ефект досягається за умови проєктування й оптимізації двигуна, силового перетворювача та алгоритму керування як єдиної електромеханічної системи.

Ключові слова: *синхронний двигун з постійними магнітами, електромеханічне перетворення енергії, енергоефективність, електропривод, векторне керування, безсенсорне керування, класи енергоефективності.*

Electromechanical energy conversion underlies industrial automation, electric transport, and renewable energy systems. As requirements for energy efficiency become stricter, attention is shifting from the electric motor alone to the whole drive: the machine, the power converter, and the control algorithm that governs them. In this context, the permanent magnet synchronous motor has become a very dependable and efficient choice for a range of industrial and automotive applications [1].

The rapid development of permanent magnet materials over recent decades enabled the design of high-performance PMSMs, which are now preferred by many manufacturers of electric vehicles [5]. At the same time, the use of magnets raises new engineering questions related to thermal behaviour, demagnetisation, additional losses, and the choice of control methods. Understanding these questions is necessary for designing drives that are efficient not only at the rated point but across the real operating range.

The purpose of the work is to examine the design features, loss mechanisms, control strategies, and efficiency standards that determine the energy efficiency of PMSM drives and to outline the main directions of their development.

Design Features and Advantages of PMSMs

In a PMSM, the excitation flux is created by permanent magnets placed on or inside the rotor, so the machine does not need an excitation winding and does not incur copper losses in the rotor circuit. Studies emphasise the exceptional torque-to-weight ratio, high power density, and reduced losses of PMSMs in comparison with conventional induction motors, which makes them the preferred choice for applications that demand precise control and high efficiency [1].

Two main rotor topologies are distinguished in the literature: surface-mounted and interior permanent magnet designs [5]. In surface-mounted rotors, the large effective air gap reduces the self-inductance of the machine, and a retaining sleeve is often used to keep the magnets in place at high rotational speeds [5]. Interior designs place the magnets inside the rotor core, which provides mechanical protection for the magnets and allows the machine to use reluctance torque in addition to the magnet torque. The choice of topology therefore directly affects the speed range, the overload capability, and the control approach.

The integration of PMSMs into electric vehicles illustrates the practical importance of these properties. According to the analysis in [1], PMSMs help to improve vehicle efficiency and reduce emissions, and their role is expected to grow with continuing advances in manufacturing and control methods.

Losses and Their Modelling

The efficiency of a PMSM drive is determined by the balance of several loss components: copper losses in the stator winding, core losses in the laminations, losses in the magnets, mechanical losses, and losses in the power converter. Core losses deserve particular attention. It has been shown that accurately predicting and mitigating core losses is essential for achieving optimal performance of permanent magnet motor drives [2]. A common approach is to use equivalent circuit models that take core losses into account, since such models combine fast computation with reasonable accuracy [2].

Importantly, these models are used not only at the design stage but also in control. By including core-loss considerations in the design and control strategies, it is possible to improve efficiency, torque production, and the overall performance of the drive [2]. This is especially relevant for drives operating at variable speed, where the share of core losses changes significantly with frequency.

In emerging high-speed applications, losses in the permanent magnets themselves and the associated heating become critical. Thermal analysis, modelling of magnet demagnetisation, and combined modelling of magnet and lamination losses are therefore treated as integral parts of the machine analysis [5]. For complex geometries, mixed numerical techniques based on the finite element method are applied to simulate permanent magnet machines with sufficient accuracy [5]. The practical consequence is that electromagnetic, thermal, and control aspects cannot be considered in isolation.

Control Strategies and Sensorless Operation

Modern PMSM drives are usually built on vector (field-oriented) control, in which the stator current is divided into a component that forms the magnetic flux and a component that forms the torque. This makes it possible to control the torque of the machine quickly and independently of the flux. Energy efficiency can then be improved by the choice of the flux or current reference, rather than only by hardware improvements.

An example of this approach is given by Ukrainian researchers who developed a direct torque control system for a two-zone electric vehicle drive based on a PMSM [6]. In the first speed range, the armature flux linkage reference is formed depending on the current electromagnetic torque of the machine in order to ensure energy efficiency, while for the second range, which relies on field

weakening, a simple method of determining the transition speed is proposed [6]. Thus, the control algorithm itself becomes a tool for reducing losses.

Another important direction is the elimination of mechanical position sensors. Position sensorless control avoids many disadvantages of such sensors, improves the reliability of the motor, and reduces costs [3]. Because no single estimation method performs equally well across the whole speed range, researchers actively develop compound sensorless control, which combines methods suited to low-speed and high-speed operation in order to achieve reliable position estimation in a wide speed range [3]. Despite this progress, the problems of accuracy at low speed and of robustness to parameter variations remain subjects of active research [3].

Efficiency Classes and Energy-Saving Potential

For the practical comparison of motors, the IEC 60034 series of standards is used. The updated IEC 60034-30-1:2025 standard has introduced IE5 as a defined efficiency class, which gives manufacturers, engineers, and end-users a clearer benchmark for specifying high-efficiency motors [4]. This is important for PMSMs, because the highest classes are typically achieved by designs based on permanent magnets or on a combination of synchronous reluctance and permanent magnet technologies [4].

According to manufacturer estimates, compared with IE3 motors, IE4 technologies can reduce energy losses by around 15–20%, while IE5 technologies can deliver reductions of 30–40%, depending on the application [4]. The effect is most noticeable in continuous-duty applications such as pumps, fans, and compressors, where energy consumption makes up a significant share of the life-cycle cost [4]. These figures should be treated as indicative, since actual savings depend on the load profile, operating hours, and the matching of the motor with the converter.

Challenges and Development Prospects

Despite their advantages, PMSM drives face a number of challenges. The first is the risk of magnet demagnetisation under high temperature and short-circuit conditions, which requires careful thermal and electromagnetic analysis at the design stage [5]. The second is the dependence of the machine on the properties and cost of magnet materials, which stimulates research into designs that use magnets more economically, including hybrid reluctance–magnet machines [4, 5]. The third is the complexity of control: to obtain maximum efficiency, the controller must account for core losses, saturation, and parameter changes, and, if the position sensor is omitted, must reliably estimate the rotor position [2, 3].

The main prospects are connected with the integrated design of the drive. Improved loss models [2], coupled finite-element and thermal analysis [5], efficiency-oriented control algorithms [6], and reliable sensorless techniques [3] together create the conditions for further reduction of losses. The growing use of PMSMs in electric transport [1, 6] and in energy-intensive industrial equipment [4] makes these directions especially relevant for the modernisation of electromechanical systems.

Thus, the energy efficiency of a PMSM drive is not a property of the motor alone but the result of the interaction of its design, the accuracy of loss modelling, and the control strategy. High torque density and reduced losses make PMSMs an effective basis for energy-saving drives, while efficiency classes such as IE4 and IE5 provide a clear benchmark for selecting equipment. The greatest effect can be expected from approaches that treat the motor, converter, and controller as one electromechanical system, which is also the main direction for further research.

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УДК 514.18:378.147

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ПРОСТОРОВА УЯВА В НАРИСНІЙ ГЕОМЕТРІЇ

Стаття присвячена дослідженню психологічних основ розвитку та формування просторової уяви студентів як вирішенню важливої педагогічної проблеми при викладанні нарисної геометрії. Проаналізовано можливості сучасних українських підручників з нарисної геометрії та інженерної графіки для розвитку просторової уяви та визначено педагогічні умови, які сприяють цьому у студентів закладів фахової передвищої освіти транспортного профілю.

Ключові слова: *просторова уява, нарисна геометрія, графічна підготовка, фантазія, понятійне мислення, підручник, комп'ютерна графіка.*

The article examines the psychological foundations of developing students' spatial imagination as an important pedagogical issue in teaching descriptive geometry. The potential of modern Ukrainian textbooks on descriptive geometry and engineering graphics for developing students' spatial imagination is analysed, and the pedagogical conditions that contribute to its development among students majoring in transport-related fields are identified.

Key words: *spatial imagination, descriptive geometry, graphic training, creative imagination, conceptual thinking, textbook, computer graphics.*

Сучасна підготовка фахівців для транспортної галузі, особливо у сфері автомобільних доріг, мостів та транспортної інфраструктури, передбачає сформовану графічну компетентність. Креслення є універсальним засобом професійної комунікації в технічній сфері, оскільки використовується під час проєктування дорожнього полотна, транспортних розв'язок, мостів, водовідвідних конструкцій, окремих вузлів транспортних засобів, а також при опрацюванні проєктної та виконавчої документації. Важливою складовою графічної компетентності є просторова уява – здатність подумки створювати та трансформувати образи об'єктів, визначати їхню форму, розміри, положення і взаємне розташування на основі плоского графічного зображення. Значну роль у розвитку цієї здатності відіграє вивчення нарисної геометрії.

Проблематика розвитку просторової уяви та психолого-педагогічні засади графічної підготовки здобувачів освіти знайшли відображення у працях В. Ананьєва, Є. Кабанової-