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Life cycle analysis of electrical motor-drive system based on electrical machine type

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Abstract. Nowadays a lot of attention is paid on the issues of global warming and climate change. Human impact on the environment is noticeable from the aspect of resource life cycles. Energy efficiency requirements have led to the research and development of alternative technologies for the rotating electrical machines. The life cycle assessment brings out important procedures which can help to reduce machines' impact on the environment, being therefore an instrument for the assessment of the influence of particular products on the environment from cradle to grave – beginning with working out the materials, followed by manufacturing, transporting, marketing, use, and recycling. Three types of electrical machines have been chosen for comparison: synchronous reluctance motor, permanent magnet assisted synchronous reluctance motor and induction motor. The article presents a life cycle assessment case study based on experimental results of motors designed by the research group.

Key words: life cycle assessment, induction motor, synchronous reluctance motor, permanent magnet assisted synchronous reluctance motor, variable speed drives, optimization, efficiency.

1. INTRODUCTION

Nowadays, global concern about the need for energy and saving Earth's natural resources is increasing. Electric motor drives (EMDs) consume 43–46% of the global electricity, which inflicts appr. 6040 Mt of CO_2 emissions per year [1]. As part of the coordinated efforts throughout the world to reduce the energy consumption and CO_2 emissions, the regulatory authorities in many EU countries have introduced the IEC 60034-30-1 legislation to stimulate the production and use of high efficiency rotating electrical machines [2]. Today there are four energy classes to describe the energy efficiency of motors: standard efficiency (IE1); high efficiency (IE2); premium efficiency (IE3); and super premium efficiency (IE4). Rising energy efficiency requirements lead researchers to develop alternative technologies for electrical machines. One possibility to reach the IE3 and IE4 efficiency class is to use rare-earth permanent magnets (PMs) in the rotating electrical machines, which in the end may lead to higher environmental footprint compared to IE2 efficiency class machines.

The integral optimization of EMD systems (incl. the use of high-efficiency and well-sized components) is the key strategy to effectively maximize their overall efficiency [3].

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Besides the energy, high efficiency rotating electrical machines require a large amount of natural resources, such as iron, copper, permanent magnet materials, and other minerals, as well as the energy needed to extract, process, manufacture, and distribute these materials. The same optimization methods are also equitable for other types of electrical machines, like transformers [4].

The EU legislation on ecodesign emphasizes the role of the life cycle of goods from raw materials to their final disposal [5]. Improving the efficiency of the EMD (and electric motor as its main part) goes on concurrently with reducing the harmful emissions emerging from the stages of production, use, and disposal. Therefore, a topical issue is the product life cycle assessment (LCA), which main principles are defined by the International Organization for Standardization: standards ISO 14040 and ISO 14044 [6,7]. The mentioned standard ISO 14040 presents the introduction into the LCA and describes its applicable specifications, containing also reference information, while the ISO 14044 regulates performance process of the LCA.

The life cycle assessment implies important procedures that can help to reduce an EMDs' impact on the environment, being therefore an instrument for assessment of the influence exerted by particular products on the environment from cradle to grave – beginning with working out the materials followed by manufacturing, transportation, marketing, use and recycling. Similar to other products, four stages can be distinguished in motor's life cycle [8]: production, distribution, use, and end-of-life.

Pollution of the environment begins with extraction of natural resources. Therefore, the production stage includes extraction of natural resources and energy sources from the Earth. Transportation of the basic material prior to its processing also belongs to this stage; the following steps are processing of the raw material and obtaining the final product. The following materials are usually used in that stage [8]: electrical copper in windings, sheet steel, impregnating varnishes and compounds, cover enamels as well as widely diversified materials of the electrical insulation (paper, cardboard, polyester films and ribbons, stratified plastics, plastic material, mica, asbestos). For producing an electric motor, the general technological processes of machine industry are applied.

The distribution stage includes all technological processes needed for packaging and transportation of the final product. The used energy and ecological wastes caused by transportation to the shopping units or to the customer are taken into account within this stage of life cycle.

The longest stage is the use stage, which also is the most expensive within the life cycle of an electric machine. The electric motors are generally designed to have the lifespan of 15–20 years without overhaul under the conditions of their normal operation. This stage is mostly associated with the customer and takes into account the actual use, the repeated use, and the service life of the product. The energy requirement and ecological wastes due to the storage and consumption are included to the use stage. In this stage, the operational efficiency of electric motor is especially important. The main parameters of the motor are its output power and efficiency. Therefore, it should be properly designed not only because of economic reasons but also from the viewpoint of ecological aspects. In the use stage, pollution is continuing mainly through overheating, generation of external magnetic fields, noise, vibration, and emissions of volatile substances from electrical materials. For example, in [9] model includes trips made due to repair and maintenance as the distance covered over the motor life (250 km).

End-of-life means the state of an electrical machine having reached the end from its first use until its final disposal. The end-of-life stage includes the energy needed for recycling the product, as well as recycling wastes, composting and burning in compliance with the relevant regulations.

According to [8] the main reasons for making LCA are as follows:

- willingness to collect the information about the ecological influence of the product or service in order to find the possibilities to reduce the environmental impact;
- necessity to explain the consumer which are the best applications of the product and methods for its recycling;
- collecting necessary information to request eco-certificates;
- comparing environmental impacts of different products.

AC Induction Motor (IM) technology has advanced fast with the progress of power electronics during the last 30 years and has been widely used in electric-motor-driven systems. A squirrel cage IM has a very simple rotor construction which increases the reliability and performance of the motor. Absence of the friction parts (except bearings) increases the efficiency of the IM. Synchronous reluctance motors (SynRMs) have simple construction and excellent characteristics of fault tolerance. These types of motors are used for dynamic applications where high torque and high speed are required, e.g., traction application. The stator and the rotor of the SynRM are made of electrical steel which is magnetized by the current through the stator winding. These motors have no windings, magnets, or cages on the rotor. An interest in SynRMs has increased, since ABB started commercial production of SynRMs for pumps, fans, compressors, extruders, conveyors, and mixers in 2012. Permanent magnets in the rotor flux barriers

noticeably improve the performance of SynRM [10] even if low-energy magnets as ferrite are used. According to the literature [11–13], the main advantage of assisting permanent magnet (PM) with the SynRM (PMSynRM) is an increase in the main torque density and in the power factor. This makes PMSynRM a promising alternative to be used in traction motor-drive systems. Current study compares three types of machines: IM, SynRM and PMSynRM [14].

2. PRODUCTION OF ELECTRICAL MACHINES (MATERIALS)

The main parts of an electrical machine are as follows: windings, cores (stator and rotor), bearings, frame, shaft, and possibly PM.

Windings of rotating electrical machines are mainly made of copper but other materials can also be used (e.g. aluminium, in case of squirrel cage induction machines). Copper is approximately three times more expensive than aluminium but it has 1.6 times higher conductivity, making it more preferable material.

Cores of electrical machine are made of electrical steel laminations that are tailored to produce specific magnetic properties: low eddy current loss, low hysteresis losses and high permeability. Laminations are separated from each other with the varnish of insulation. Electrical steel is an iron alloy where silicon has been added. Silicon is added to the material to reduce the conductivity of the material, resulting in lower eddy current losses, and to narrow the hysteresis loop, resulting in lower hysteresis losses. The amount of silicon added to the commercial alloy is usually up to 3.2%, higher concentrations may provoke brittleness during the cold rolling [15]. The electrical steels used in electrical machines are non-oriented and grain-oriented in case of transformers.

One alternative to the electrical steel laminations is the use of soft magnetic composites (SMCs), which can be described as ferromagnetic powder particles surrounded by an electrical insulating film [16]. SMC provides magnetic properties such as good relative permeability and magnetic saturation, and high electrical resistivity. The size of the particles is typically 5–200 µm, the thickness of laminations is normally 200–1000 µm [17]. SMC offers several advantages over traditional electrical steel. For example, the isotropic nature of the SMC, combined with the unique shaping possibilities, opens up for 3D-design solutions, meaning that it is possible to lead the flux in three dimensions. SMCs have several advantages, such as reduction in weight and size. On the other hand, SMC materials are characterized with high core losses compared to the lamination, at least for frequencies less than 1 kHz. Moreover, the unsaturated

magnetic permeability of SMC is lower than that of unsaturated electrical steel. The SMC material is the most appropriate for using in high speed PM machines, for which the magnetic reluctance of the magnet dominates the magnetic circuit, making the performance of such motors less sensitive to the core permeability [17].

Rolling bearings used in electric machines are to support and locate the rotor, to keep the air gap small and consistent, and to transfer loads from the shaft to the motor frame. Bearings in electrical machines should have minimal friction and they should be hardwearing, which means that the materials should match specific requirements regarding strength and dimensions. Materials used for producing bearings depend on electrical machine size and design, as well as on the operation properties like speed and environment. Metal bearings are usually made of chrome steel, stainless steel or carbon alloy steel. Some manufacturers provide electrically insulated bearings to prevent current from passing through the bearing. Such bearings can be made of plastic for low power electrical machines, or of ceramics for high power electrical machines. These bearings can improve the reliability and increase machine uptime by virtually eliminating the problem of electrical erosion [18].

For shaft production, most electrical machines man-ufacturers use carbon steel SAE 1045 (cold-rolled or hot-rolled). SAE 1045 is a medium carbon, medium tensile steel, supplied in a forged or normalized condition. SAE 1045 shows good strength, toughness and wear resistance. It is widely used for bolts, axles, forged connecting rods, crankshafts, light gears, guide rods, etc. Some other materials used for electrical machine shaft production are for example SAE 1117, SAE 1137, SAE 1144, hot-rolled SAE 1035, and cold-rolled SAE 1018.

Stator of the electrical machine is fixed to the frame and rotor, which is arranged to rotate around its axis, is connected to the frame by rolling bearings. Usually, the frame of the electrical machine is equipped with cooling ribs for passive cooling or built-in liquid cooling system for active cooling. The frame of any electrical machine is usually made of non-ferrous aluminium alloy. In the past, cast-iron alloys were also used [4].

Using PM in electrical machines presents an opportunity to build energy efficient machines. There are three classes of PMs currently used for electrical machines [19]:
- alnicos (Al, Ni, Co, Fe);
- ceramics (ferrites), i.e., barium ferrite $BaO \times 6Fe_2O_3$ and strontium ferrite $SrO \times 6Fe_2O_3$;
- rare-earth materials, i.e., SmCo (samarium-cobalt) and NdFeB (neodymium-iron-boron).

The remanence and coercivity of NdFeB is higher than of any other type of PM. Despite of large advantages,

neodymium (Nd) magnets have a relatively low Curie temperature, which is a great disadvantage in comparison with other types of magnets. Adding another rare-earth element, such as dysprosium (Dy), helps to increase the maximum temperature range, which is important for the electric motors. Adding of small amount of Dy leads to the significant magnet cost increase, because Dy is rarer and seven times more expensive than Nd [20,21].

Magnets made of rare earth elements have given a push forward in the development of PMs. SmCo magnets have usually been too expensive to be used in classical electrical machines. At the same time, NdFeB magnets are more favorable than SmCo magnets regarding energy density, but their problem has been heat endurance. However, over the last decade, NdFeB magnets have been evolved greatly, showing improvements in endurance capacity of heat and corrosion. This makes them one of the most used magnetic materials in large electrical machines. Consumption of rare earth elements has been rising due to their use in wind generators and lately also in drives of electric vehicle. However, the supply with present consumption should be available for more than 1000 years [21].

The amount of materials used in the machines depend on the machine ratings and the types of the machines. Different types of machines can be compared based on the percentage values of the materials used in there. For example, the percentage ratio of raw materials used for 10 kW motors [8] is presented in Fig. 1. It can be seen from the figure that the main material used in the machines is the electrical steel, the next is aluminium, which is used for machine frame. The third material is the non-conductive (incl. insulation and packing) material, which includes winding insulation, impregnation resin,

paint, etc.; then comes copper, and finally other materials and permanent magnets. The rotor winding of IM consists of parallel conductors and end rings, which are welded, electrically braced, or even bolted at both ends of the rotor. The rotor of SynRM consists of soft magnetic material, which has multiple projections acting as salient poles through the magnetic reluctance. In PMSynRM the projections are filled with PM bars.

The materials used for manufacturing motors, using geometric modelling of the reference motors, are presented in Table 1. The SynRM and PMSynRM type motors are similar in design, the only difference is that PMSynRM has permanent magnets in the rotor air barriers. It should be noted that the available permanent magnets make the design heavier and more expensive.

Table 1. Bill of materials for motor production

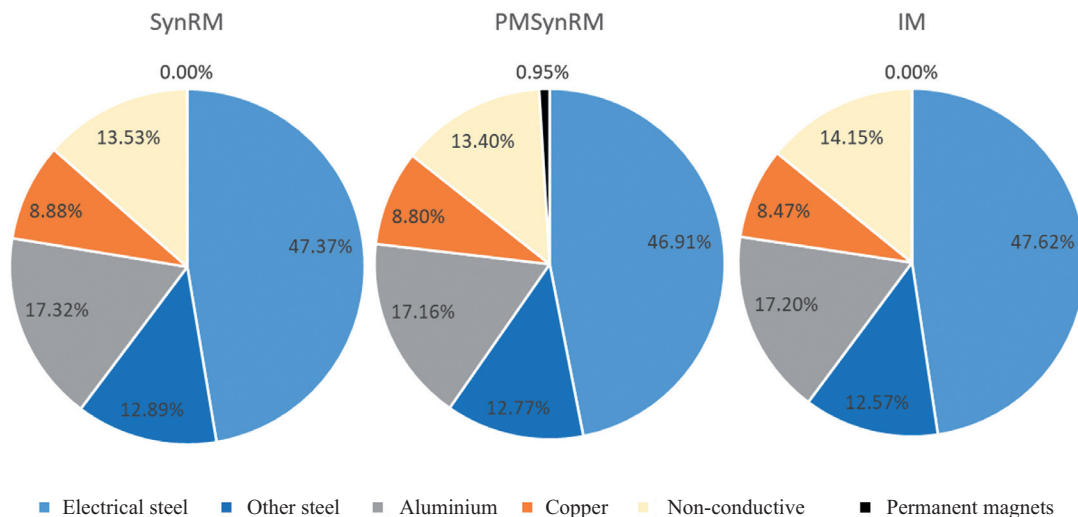| Material	Weight (kg)		
	SynRM	PMSynRM	IM
Electrical steel	34.900	34.900	36
Other steel	2.11	2.110	9.500
Aluminium	12.764	12.764	13
Copper	6.546	6.546	6.400
Insulation material	0.200	0.200	0.200
Permanent magnets	–	0.710	–
Impregnation resin	0.470	0.470	1
Paint	0.302	0.302	0.500
Packing material	9	9	9

Fig. 1. Percentage ratio of raw materials used for different 10 kW motors production.

3. USE STAGE OF ELECTRICAL MACHINES

Use of variable-speed drives (VSDs) in variable-output applications may lead to large energy savings [3]. The number of losses in electric-motor-driven systems are associated with starting method and its own losses, including extra harmonic losses (e.g., due to the harmonic distortion) for VSD. The main parts of any AC VSDs are the frequency converter and the electrical machine. Addressing the topic of losses in the frequency converter is not possible without considering losses in the machine itself. Loss analysation process must be implemented for the whole system to ensure that reducing losses only in the frequency converter will not increase the losses in the machine and vice versa. Thus, it is important to clarify the loss mechanism in the studied machines. The natures of the losses in these machines are identical and are comprised of iron losses (hysteresis and eddy-currents), copper losses, mechanical and stray load losses. Apart from engaging loss minimization problem through the machine design, control techniques are proposed to reduce losses during operation [22]. The research on the simultaneous losses' evaluation of the machine and the drive shows that the question is approachable and needs consideration.

In this study, the efficiency maps of designed SynRM and PMSynRM were compared to the efficiency of an industrial IM, including the separate analysis of frequency converter efficiency and full EMD comparison. The stator part of all three studied motors is the same, the main difference in construction and materials comes from the rotor part, as shown in Fig. 2. Compared machines have the same standard frame size (132) and custom stator winding, in order to avoid saturation in the yoke region.

The stator of the tested machines includes temperature sensors, which were used for hybrid thermal model of SynRM [23], to calculate and evaluate the temperature of the machine.

3.1. Test setup

In order to have a reasonable comparison, all three studied electrical machines were driven by a 30-kW industrial frequency converter (ABB ACS880) with the same control algorithm Direct Torque Control (DTC). An IM fed by 37 kW frequency converter (ABB ACS800) setup was used as a load. For testing purpose, the load torque is gradually increased from zero to the calculated rated load torque in a ramp mode. All experiments were performed in a real-time setup including motors and frequency converters.

Considering the same frequency converter, the same control method, and the same measurement system for each motor, the comparison between three studied motors in terms of efficiency of the whole motor drive system is composed. The line currents are precisely measured in terms of total magnitude and harmonics. To measure the total current and low frequency current harmonics, the Fluke 1400s AC current clamps were used. The voltages are directly measured by the universal data acquisition measurement system Dewetron in both terms of fundamental magnitude and low frequency harmonics. The measured signals were used to calculate the frequency converter input power and frequency converter output power in Dewetron measurement system. To eliminate measurement error, measured values were re-checked with Fluke 434 energy analyser to accredit the initial measured values. Motor's speed and torque were measured by NCTE torque transducer, which is mechanically coupled between the loading and testing motors. Measurement system works with 10 kHz sampling frequency. The parameters of the motors are shown in Table 2.

Fig. 2. Rotors of the tested electrical machines front view.

Table 2. Rated parameters of the studied motors

Parameter	SynRM	PMSynRM	IM
Frame size	132 MA	132 MA	132 MA
Power (kW)	10.5	10.5	10.5
Current (A)	22	23.6	22
Speed (rpm)	1500	1500	1460
cosϕ	0.6	0.96	0.79
Moment of inertia (kgm^2)	0.048	0.048	0.048

3.2. Efficiency maps comparison

For comparison, efficiency maps in the constant torque region of the motors were composed. Efficiency maps of the studied motors, feeding frequency converter, and the whole drive system are shown in Figs 3, 4 and 5, respectively.

Ratio of the motor shaft power (P_{mech_motor}) to the total output power ($P_{conv\_out\_total}$) of the frequency converter is taken as motor efficiency (η_{motor}):

$$\eta_{motor} = P_{mech\_motor}/P_{conv\_out\_total}. \quad (1)$$

Frequency converter losses consist of switches conduction losses, switches turn-off losses, conduction losses in the diodes, magnetic component losses, capacitor losses [22]. Ratio of the converter total output power to the total input power ($P_{conv\_out\_total}$) is taken as power converter efficiency (η_{conv}):

$$\eta_{conv} = P_{conv\_out\_total}/P_{conv\_in\_total}. \quad (2)$$

Ratio of motor shaft power to total input power is taken as motor drive system efficiency (η_{drive}):

$$\eta_{drive} = P_{mech\_motor}/P_{conv\_in\_total}. \quad (3)$$

PMSynRM shows better performance compared to the SynRM and IM, which could be interpreted due to the presence of PM. The maximum motor efficiency (92.3%), along with the wider region of maximum efficiency, makes PMSynRM more usable for wide range of applications. SynRM and IM have very similar performance indicators (89.2% for SynRM and 88.5% for IM), however SynRM has a wider region of maximum efficiency. Such behaviour could be interpreted by copper losses in the machine. The power dissipated in the stator and rotor windings due to the resistance wire, is lower in case of SynRM, as it has no conductive winding on the rotor.

This high efficiency for frequency converter (above 95%) covers the whole operating region in all three case studies. However, it can be seen that the optimal working
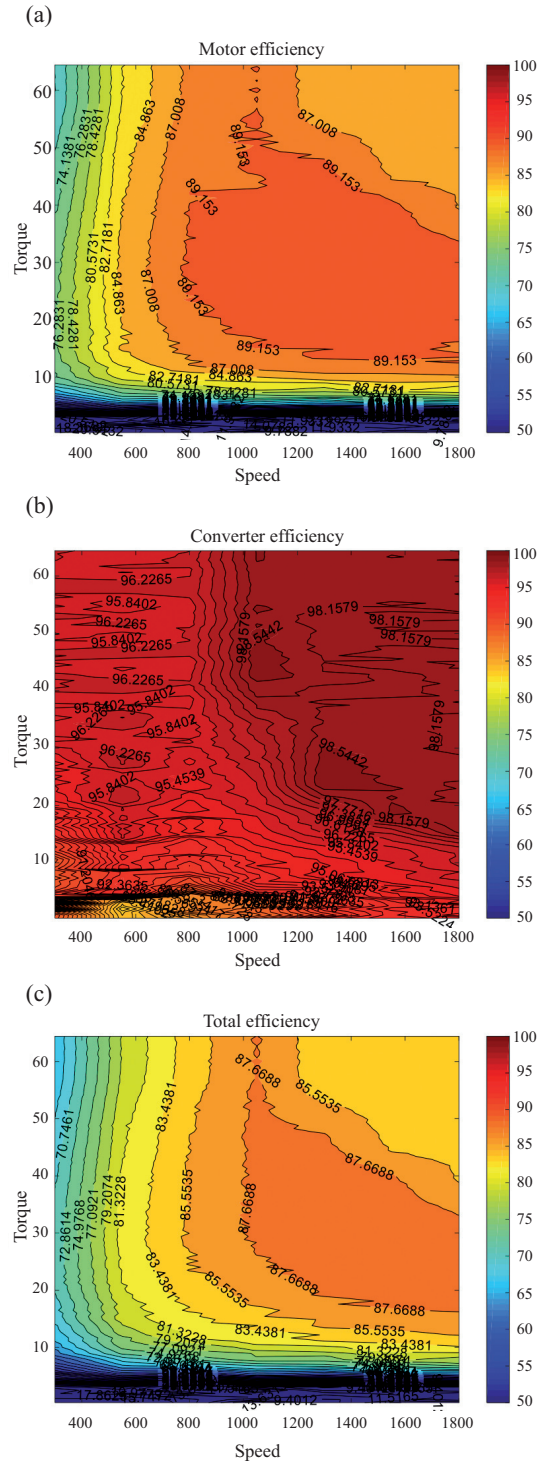

Fig. 3. Efficiency maps of the studied SynRM (a), feeding SynRM frequency converter (b), and the whole SynRM motor-drive system (c).

region is located between 20.65 Nm and 1000–1800 rpm for this test. Such behaviour could be interpreted as the tests use an overdimensioned frequency converter (see chapter 3.1).
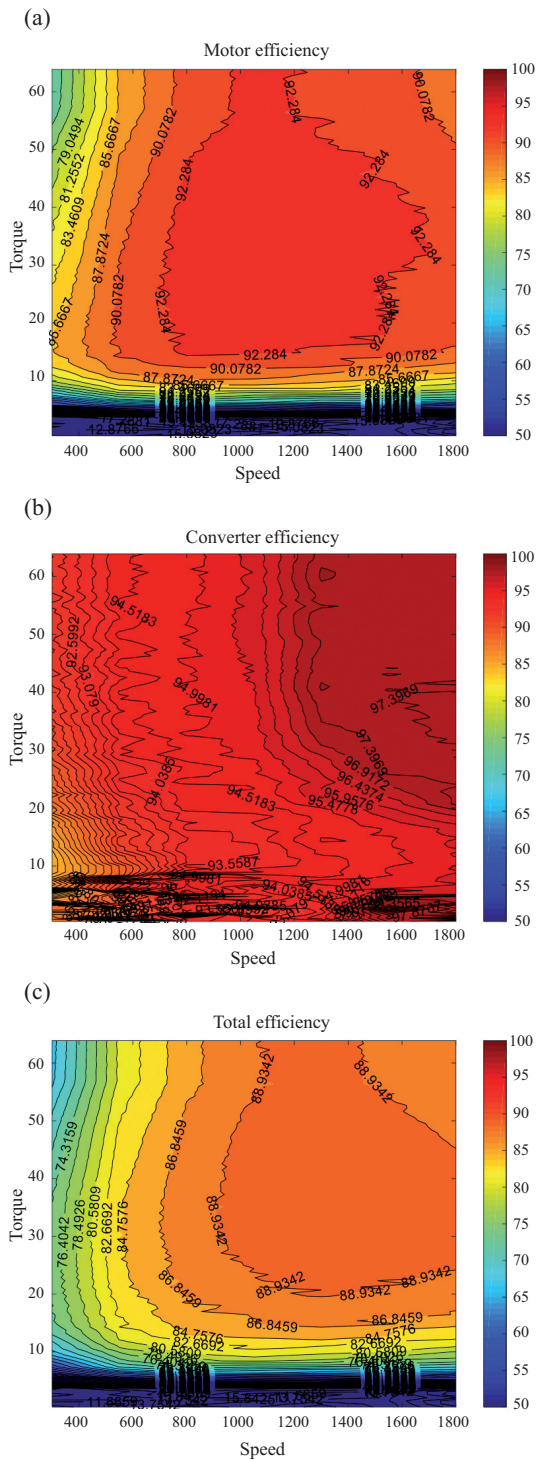
Fig. 4. Efficiency maps of the studied PMSynRM (a), feeding PMSynRM frequency converter (b), and the whole PMSynRM motor-drive system (c).
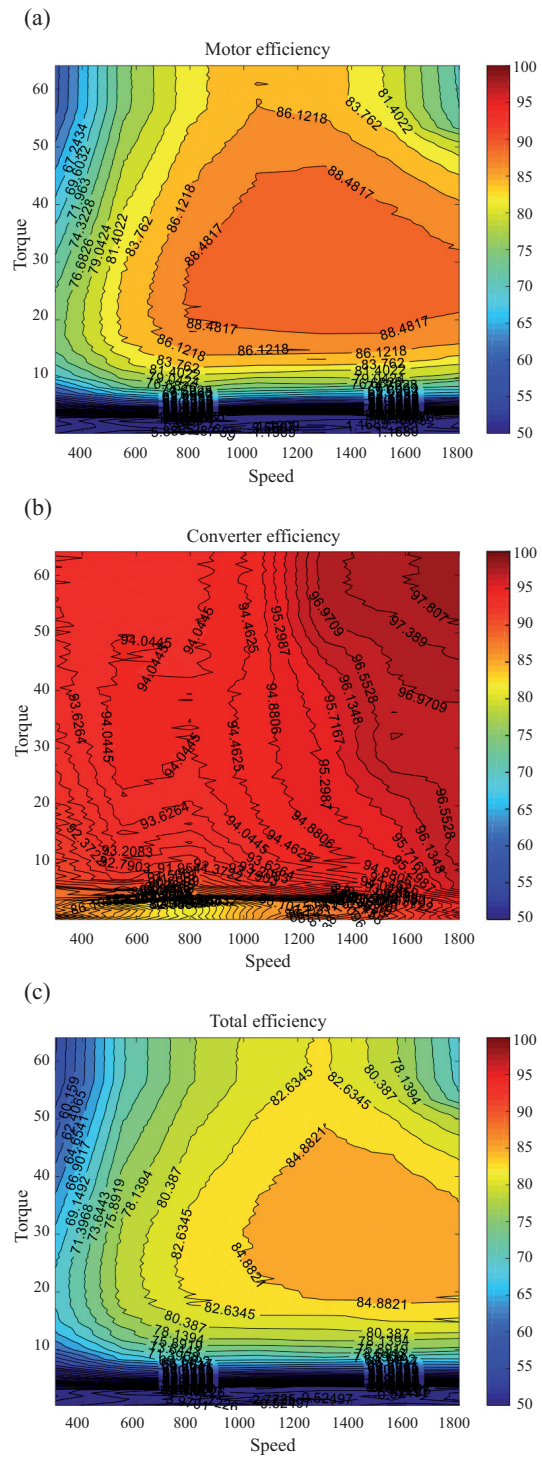
Fig. 5. Efficiency maps of the studied IM (a), feeding IM frequency converter (b), and the whole IM motor-drive system (c).

It can be clearly seen that the motor-drive system efficiency resembles the motor' efficiency, which implies to the motor's large effect on the whole system.

4. REUSE AND RECYCLING OF STUDIED ELECTRICAL MACHINES

Human activities have caused noticeable effects on the environment from the perspective of resource life cycles, starting from consumption of resources and caused pollution up to the waste products and recycling. Wastes composed of electrical and electronic equipment such as computers, TV-sets, fridges and cell phones, are one of the fastest growing waste streams in the European Union (EU), with appr. 9 million tons generated in 2005, and expected to grow to more than 12 million tons by 2020 [24]. The economic instruments adopted by the EU to promote waste disposal are disposal fees implemented by the European Waste Electrical and Electronic Equipment Directive (WEEE Directive). Part of equipment such as electric motors, transformers, variable speed motor drives, etc. are not falling within the scope of WEEE Directive [25]. It is estimated that more than 53% of the globally consumed electricity is used in electric motor systems in industry, building industry, agriculture and transportation [26].

4.1. Recycling methods

There are only few methods of recycling electrical machines: shredding or disassembling. The method used for recycling depends on the size of the recycled electrical machine and from the recycled components. After disassembling, some parts of the electrical machine could be reused directly and other parts should be remelted to get the same raw material or to make a new alloy.

Today, the main way of recycling small electrical machines is based on shredding. During the shredding procedure, the electrical machines are cut into small pieces and sorted automatically or manually. There is also a risk that different materials will be mixed during shredding procedure and will not be properly separated [27]. Nonferrous metals can be detached from iron materials by magnetic separation but even small-scale mixing of the materials gives negative effect. For example, the recycled iron has a copper content of 0.25–0.3%, which makes it useless for high-grade iron. In order to have a good quality iron, the copper content has to be lower than 0.02% [17].

More powerful electrical machines that are too big for shredding and can damage the grinder, are handled separately [28]. Disassembly of powerful electrical machines can be performed manually, using robots or in combination of both. Difficulties of automated disassembly are deformed shapes of some electrical machines. On the other hand, manual disassembling has high labour costs. As the studies show [29], the best results of disassembling can be achieved when using the optimization models constructed by prioritization of the components and the materials of the product. Separate parts of disassembled electrical machines can be reused in case they do not have any damages and are not worn out.

Disassembling technique is highly dependent on the electrical machine construction. For example, magnets of PM assisted electrical machines are either mounted on the surface (surface-mounted PM) or in pockets close to the rotor surface (integrated PM). In case of integrated PM, the magnets can be damaged during disassembling. Direct reuse of PM is only possible for large, easily accessible magnets used in wind turbines and possibly in large electric motors and generators in hybrid and electric vehicles; unfortunately, they are not available in large quantities in scrap today [30]. After disassembling and, if necessary, demagnetization, PM can theoretically be processed in a recycling plant. Withal, currently the recycling of NdFeB magnets does not exist outside China [31], where production wastes are mainly recycled. Recycling processes for NdFeB magnets often target sintered, rather than bonded magnets, since these are of greater recycling value owing to their high energy product [32]. Some other recycling methods for rare earth PM's are reprocessing of alloys to magnets after hydrogen decrepitating, hydrometallurgical methods, pyrometallurgical methods or gas-phase extraction [30].

The life of a rolling bearing is expressed as the number of revolutions or the number of operating hours at a given speed that the bearing is capable of enduring before the first sign of metal fatigue (spalling) occurs on a raceway of the inner or outer ring or a rolling element [33]. The bearing industry uses different materials for the production of the various bearing components. These materials are processed to achieve desirable properties to maximise bearing performance and lifespan. Rolling bearings cannot be reused directly due to the wear and friction, and remelting is the only way to recycle rolling bearings.

The main parameter of electrical machine winding is the quality of insulation. Life cycle of the insulation is usually around 25–30 years, it is very sensitive to temperature changes and is exposed to aging. Due to this, the copper windings of electrical machines are always remelted after disassembling.

Some researchers present modular construction of electrical machines [34–37]. The main benefit of such modular construction is that the electrical machines can be easily dissembled and damaged parts may be replaced

or functioning parts can be separately reused in other electrical machines of that type. Moreover, there are some solutions for direct reuse of rare-earth PMs [38] that offer the reuse of small, unit-cell (segmented) magnets to replace the normal solid-pole configuration.

The scope of end-of-life products extraction of electrical machines adopted in this research is shown in Fig. 6. Electrical machines recycling from the end-of-life products comprises of the following steps:

- the collection process for disposed end-of-life products;
- the process for transporting the removed units to the location of disassembling, where rotor, stator, windings and magnets are removed from the units;
- sorting electrical machines according to their type, power range, dimensions;
- the unit disassembly or shredding process for removing the component containing metals and rare-earth magnets out of the units;
- the process for extracting metals and PMs (e.g. NdFeB or SmCo) from rare-earth elements.

The largest negative environmental impact is caused in case the electrical machine is not recycled. Depending on the recycling method, electrical steel can be more environment-friendly but has higher labour costs due to direct reuse, or has higher environmental impact and higher economical profit using shredding. The fact that electrical steel is the iron alloy with very specific properties does not have any specific value. Any kind of reuse of the electrical steel, except direct reuse, is affecting properties of the material and it cannot be reused as electric steel without metallurgical recuperation. Each step of the electrical steel process chain has an impact on the microstructure evolution, e.g., grain size and magnetic texture, which determines the electromagnetic properties [40]. The copper and aluminium that have been used for the electrical machine winding cannot be reused directly, because of the conductive parts insulation. The only solution is remelting, but in this case, the remelted copper/aluminium will contain impurities which will decrease the quality of raw material. In this case, economical profit highly depends on the costs of melting and processing energy and labour costs, moreover material losses should be considered. The only way to reuse non electrical steels in electrical machines is melting, while during the use stage the parts made of iron are usually wearing out (shaft, frame, bearings, etc.). In this case, steel alloys lose their features and after recycling, raw steel should be processed once again (e.g. hardening). This results in higher environmental impact. Nowadays, environmental impact of PMs is not taken very much into account. Environmental impact could be decreased by using some advanced recycling methods [39].

4.2. Cost aspects and environmental impact

There are very few researches made on the environmental impact of electrical machines during their disposal stage. For example, in [41] for 10 kW IM it is considered that aluminium, copper and steel are recycled to the extent of 70%, 70% and 45%, respectively, and the remaining waste is incinerated and buried in the range of 53% and 47%, respectively. Recovery amount of metals and rare-earth magnets are an important factor in the appraisal of recycling costs. Thus first, the costs of the recycling should be estimated and then compared to the number of products obtained from the electrical machines. Study that takes into account cost of materials in 2018 is presented in [39]. Figure 7 shows percentage ratio of raw material price based on different 10 kW motors production. If the price of IM raw materials makes 100% the price of producing, IM and SynRM are almost equal (100% and 98%, respectively), but considering the price of PM, the same price for PMSynRM would be 118%.

It should be mentioned, that this is valid for studied 10 kW electrical machines, in the case of very large electrical machines (above 1 MW), the mechanical aspects [42] and such factors as power density [43] are more important.
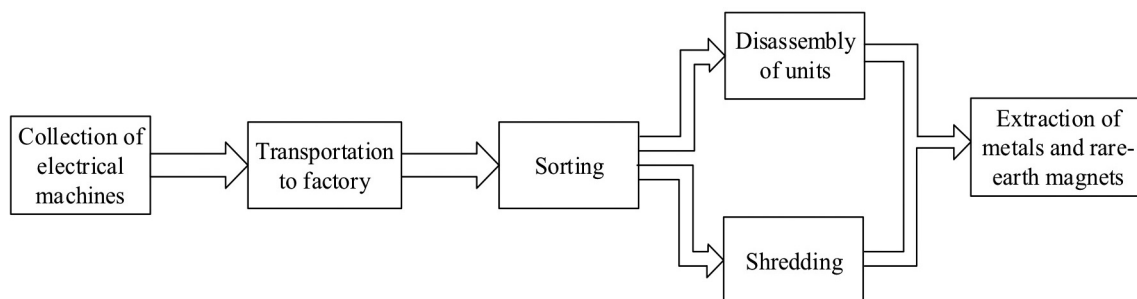

Fig. 6. Evaluation of electrical machines recycling for end-of-life products extraction [39].
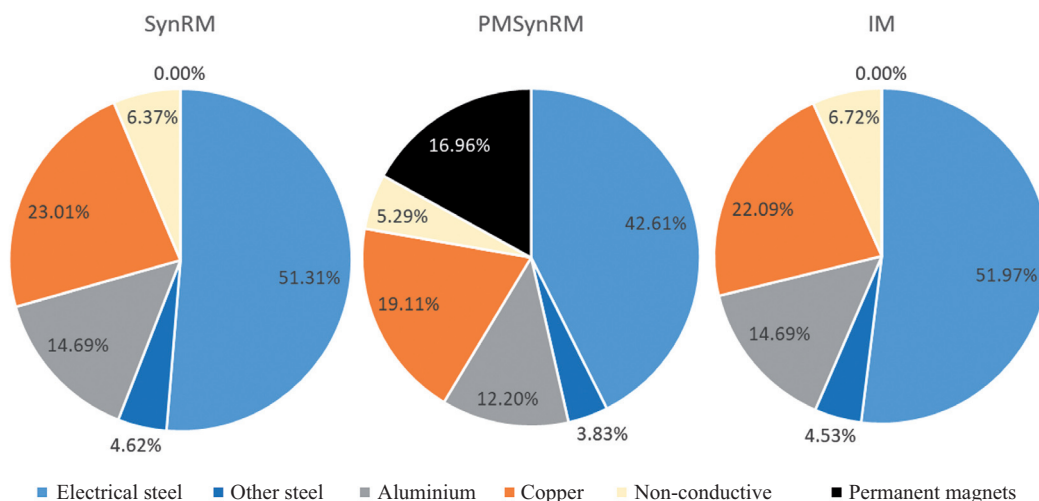
Fig. 7. Percentage ratio of raw material price based on different 10 kW motors production.

Commonly, SynRM and IM do not have any rare-earth elements and can be shredded. Different materials in the product will be mixed in during the shredding procedure, although nonferrous metals could be detached with magnetic separation. PMSynRMs contain relatively high concentration of valuable compounds like PM magnets, which suffer from poor recycling efficiency during shredding. This means that disassembling will be the main recycling method for such electrical machines.

5. LIFE CYCLE ANALYSIS OF STUDIED ELECTRICAL MACHINES

5.1. Life cycle assessment

In [8], the comparison of life cycle assessment (LCA) was made in view of the related environmental impact. Methodology for the Ecodesign of Energy-using Products (MEEuP) was selected and applied for the current research. MEEuP was worked out to determine whether and to what extent a product meets the criteria stipulated in the Directive on the Ecodesign of Energy-using products (EuP 2005/32/EC) [44]. MEEuP analysis requires the following inputs [45]: bill of materials and manufacturing processes; performance, consumption and emission characteristics during the use stage; distribution characteristics (volume of the package of the final product, transport mix); end-of-life characteristics (recycling and waste disposal).

The MEEuP methodology provides a tool for estimation of the environmental impact. In the preparatory stage, the economic data, material and energy use data were collected to make an input to the relevant model with different stages of a product's life cycle. The model translates these inputs into quantifiable environmental impacts.

The results of MEEuP analysis are presented as a list of environmental indicators [45]: energy, water (processing and cooling); waste (hazardous and non-hazardous); global warming potential (GWP); acidification potential; volatile organic compounds (VOC); persistent organic pollutants (POP); heavy metals (to air and water); polycyclic aromatic hydrocarbons (PAH); particulate matter; water eutrophication potential of some substances; ozone depletion potential. More information about emissions which have been taken into account in this paper, is given in Appendix.

5.2. Results of the comparative analysis of IM, SynRM and PMSynRM

The input data for SynRM and PMSynRM are calculated based on Table 1, input data for IM were taken from the EuP Base case [46].The major materials used for electric motors (e.g. steel, aluminium, copper) are recyclable and have a very high value, hence, they are recycled at the end-of-life [39].

According to [46], some design recommendations can be made to improve the environmental impact of electric motors: motors should be easily assembled and disassembled; a reduction of the diversity of materials used should be sought; a reduction of non-recyclable parts, namely plastic, should be achieved; windings should be easily removable.

Table 3 presents the parameters important for the use stage: the lifetime of a motor (considered to be 15 years), its operating hours, efficiency, and output power.

Table 4 presents the indicators of the environmental impact made by the motors (lifetime 15 years, operation 3000 h) during their life cycle. The life cycle indicators are divided into three blocks: main indicators, emissions

Table 3. Parameters important for the use stage of motors

Parameter	SynRM	PMSynRM	IM
Lifetime (years)	15	15	15
Operating (hours)	3000	3000	3000
Efficiency (%)	89.2	92.3	88.5
Output power (kW)	10	10	10

Table 4. Life cycle indicators of the environmental impact made by the motors

Main indicators	SynRM	PMSynRM	IM
Gross Energy Requirement (GER)(MJ)	677 883	531 180	546 584
of which, electricity (in primary MJ)	673 562	526 625	541 570
Water process (l)	47 740	37 972	38 894
Water cooling (l)	1 793 031	1 401 174	1 439 963
Waste, non-hazardous landfill (g)	961 094	792 773	838 025
Waste, hazardous incinerated (g)	15 967	12 582	13 388
Emissions into air	**SynRM**	**PMSynRM**	**IM**
Greenhouse gases in Global Warming Potential for time horizon of 100 years (GWP 100) (kg CO_2 eq.)	23 120	22 344	23 304
Acidification, emissions (g SO_2 eq.)	177 857	140 064	144 359
Volatile organic compounds (VOCs)(g)	262	210	217
Persistent organic pollutants (POPs)(ng i-Teq)	5 455	4 522	4 886
Heavy metals (mg Ni eq.)	23 598	21 112	25 216
PAHs (mg Ni eq.)	1 590	1 306	1 344
Particulate matter (g)	4 488	4 172	4 362
Emissions into water	**SynRM**	**PMSynRM**	**IM**
Heavy metals (mg Hg/20)	7 730	6 784	6 883
Eutrophication (g PO_4)	146	142	165

into air and emissions into water. It should be noted that a loss-based environmental impact assessment is presented in Table 4, in [8] electric motor is defined as energy converter (not as end-user device).

Greenhouse gas bar charts are shown in Fig. 8. Greenhouse gases are those that absorb and emit infrared radiation in the wavelength range emitted by the Earth.

As follows from Table 5, the use stage completely dominates the life cycle impact of electric motors, and it is directly dependent on the efficiency of the designed motor. This stage is the most involving from the ecological and economical points of view. MEEuP model considers the distance of the first trip from manufacturer (or retailer) to the installation site (250 km) [46] to be the distribution stage. This does not include the distance covered by trips made due to the repair and maintenance of the motor.

6. DISCUSSION

It is very difficult to estimate the exact price of recycling of the electrical machines, while the particular parts (labour costs, material costs, energy costs, etc.) of total price vary from country to country, or even from factory to factory. Raw materials received during recycling can be reused directly, remelted into different alloys or used in powder metallurgy for further production. The steps described in Chapter 4 are designed to increase efficiency of material reuse in order to achieve low recycling cost and high recycling rates.

It is clear that the efficiency of the motor-drive system mostly depends on the motor's efficiency. According to the general formula of the torque in an electrical machine, the torque is proportional to the electrical loading and the
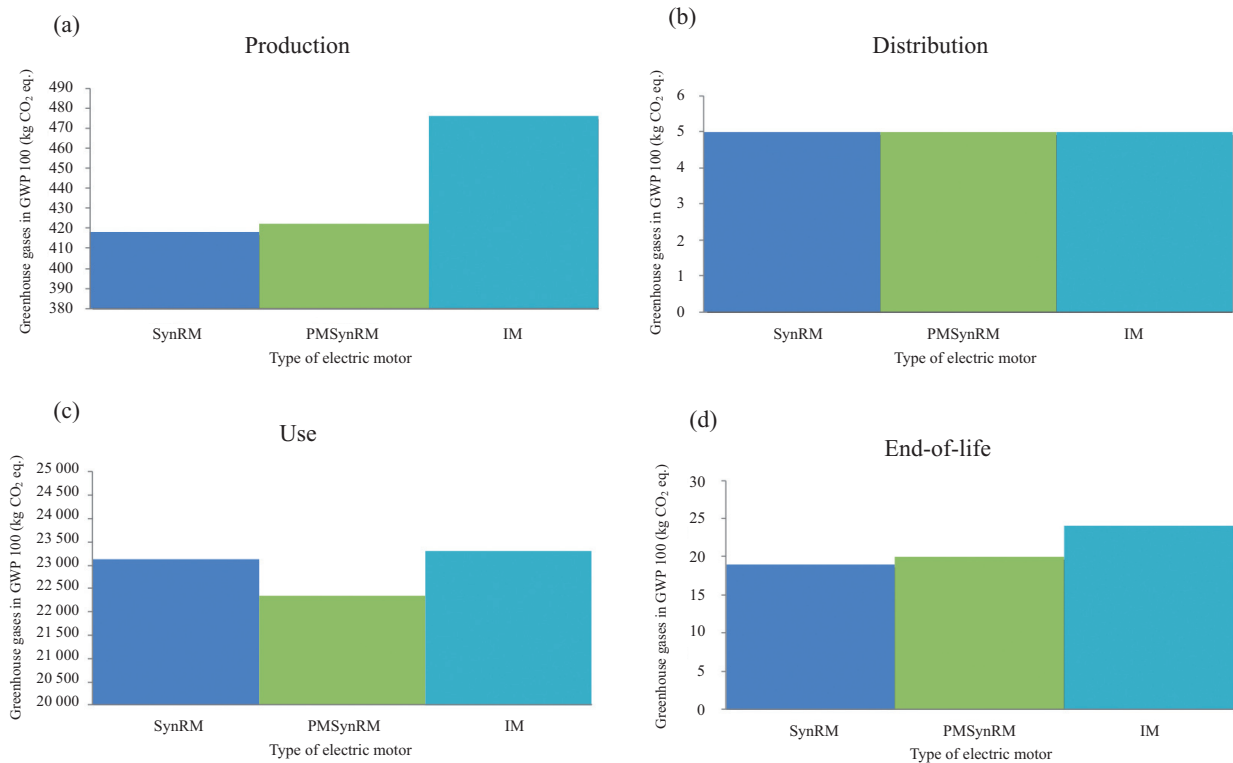
Fig. 8. Greenhouse gases vs. the type of electric motor in four life cycle stages: production (a), distribution (b), use (c) and end of life (d).

Table 5. Environmental impact made by the motors in different life cycle stages

Stage	SynRM	PMSynRM	IM
Production (%)	1.77	1.85	2.00
Distribution (%)	0.02	0.02	0.02
Use (%)	98.12	98.04	97.88
End-of-life (%)	0.08	0.09	0.10

magnetic loading [23]. To increase the torque, the electrical and magnetic loadings must be increased. However, due to the saturation of the stator iron at high flux density, the only practical way of increasing the torque is increasing the electrical loading, which can be achieved by increasing the current density. Higher current density means higher copper losses, as well as lower efficiency. Study [47] shows, that design of the electrical machine (particularly SynRM and PMSynRM) is continually enhanced by taking the efficiency map of the motor as a reference.

From the four stages of the motor life cycle described in Chapter 5, the production stage is less costly for the SynRM, as there are no high-energy magnets and the rotor is without winding. Respectively, the raw materials used in production are cheaper and have lower environmental impact. However, this type of motor produces a huge amount of waste during the use stage due to its low efficiency. Motors with low efficiency have high utilization cost and high rate of emissions. Regarding the PMSynRMs, it should be noted that although the use of permanent magnets makes its design expensive and heavy, this type of motors inflict less damage to the environment during the use stage.

The next step of the research is to improve the overall performance of the SynRMs and PMSynRMs by implementing different optimization techniques. Decreasing the losses is a key optimization methodology of any optimization algorithm, a review of the PMSynRM losses and thermal analysis are presented in detail in [48]. Moreover, additive manufacturing [49,50] is offering new optimization solutions for electrical machines.

Digital Twin [51] concept is a useful tool for energy optimization of EMD system, including electrical machine as the main component. Digital Twin can predict the future

performance, behaviour and maintenance of a complex system, it is not only an emulation or simulation of the physical object with its development history but it also contains information from the connecting manufacturers and services.

7. CONCLUSIONS

The LCA allows to compare the different products and give the opportunity to say which of them is more environment friendly, not only in production stage, but also considering the entire life cycle period.

In the future it is not possible to produce the product without knowing the product's impact on the environment. The producers should know what happens before and after the production stage in the factory.

The assessment of the expected environmental impact should be done in the early design stage, which would enable to decrease harmful emissions into the atmosphere.

The PMSynRMs are the most expensive machine types amongst the compared ones from production life cycle stages, while in the use stage they inflict lower environmental impact.

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APPENDIX

Greenhouse gases (GHGs) are the group of gasiform compounds, which are components of the Earth atmosphere. They practically do not pass through the thermal radiation coming from our planet. The following compounds are included into the GHG list: water vapour, carbon dioxide (CO_2), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFC), sulphur hexafluoride (SF_6).

Acidification is caused mainly by emitting the oxidizing substances – ammonia (NH_3), sulphur dioxide (SO_2), and nitrogen (N). The emissions of the acidifying substances cause serious damage to the environment and humans.

Volatile organic compounds (VOCs) are the chemical substances emitted to the atmosphere, in combination with nitrogen oxide (NO) and ozone (O_3). These are chemical substances whose initial boiling point measured at the standard pressure is 101.3 kPa or 250 ^{o}C.

Persistent organic pollutants (POPs) are the primary or by-products of the industry. Nowadays, 12 substances are designated as POP: polychlorinated biphenyls ($C_{12}H_4C_{14}O_2$) and furans (C_4H_4O), polychloride biphenyls ($C_{12}H_{10-n}Cl_n$), DDT ($C_{14}H_9C_{15}$), chlordane ($C_{10}H_6Cl_8$), heptachlor ($C_{10}H_5Cl_7$), hexachlorbenzene (C_6Cl_6), toxaphene ($C_{10}Cl_{12}$), aldrin ($C_{12}H_8Cl_6$), dieldrin ($C_{12}H_8Cl_6O$), endrin ($C_{12}H_8Cl_6O$), and mirex ($C_{10}Cl_{12}$). As a rule, the POPs have common characteristics: they are low-volatile chemically stable compounds, which are able to remain in the environment for a long time without being decomposed.

Heavy metals and their compounds stand out within the various polluting substances by prevalence, high toxicity, many of them also by the ability to bioaccumulation. They are widely used in various industries, so despite the clean-up procedures the content of heavy metals in the industrial wastewater is rather high. They also enter the environment from the domestic wastewater, smoke and dust of industrial enterprises.

Polycyclic aromatic hydrocarbons (PAHs) are high molecular weight organic compounds of the benzene series, differing in the number of benzene rings (2 to 7). The technology-related PAHs are formed during the combustion of fossil fuels in the industry and energy economy when producing coke or operating the internal combustion engine.

Eutrophication is the saturation of water reservoirs with biogenic elements, accompanying the increase in the biological productivity of water reservoirs. The eutrophication can be a natural result of the aging of the reservoir, as well as due to anthropogenic impacts. The main chemical elements contributing to the eutrophication are phosphorus (P) and nitrogen (N).

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Elektrimasinapõhine elektrimootorajami elutsükli analüüs

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Tänapäeval pööratakse järjest enam tähelepanu kliima muutuste ja soojenemise põhjustele. Inimmõju kliimale väljendub märgatavalt tehnoloogiliste seadmete ressursitõhususes ja tööeaga arvestamises. Energiaefektiivsuse nõuded on elektrimasinate puhul viinud alternatiivsete tehnoloogiate arenguni. Tööea hindamine toob välja tähtsaid protseduure, mis aitavad masinate mõjusid keskkonnale vähendada. Tööeapõhiselt on võimalik hinnata masinat "hällist hauani" ehk alustades toormaterjali hankimisega ja jätkates tootmise, transpordi, müügi, kasutuse ning taaskasutuse või utiliseerimise hindamisega. Võrdluseks on valitud kolm elektrimasina tüüpi: sünkroonreluktants-, püsimagnetitega sünkroonreluktants- ja asünkroonmootor. Artiklis on esitletud tööeapõhise hindamise juhtumiuuringut, mis põhineb teadusrühmas projekteeritud elektrimasinate katsetuste tulemustel.