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# RE-USE AND RECYCLING OF DIFFERENT ELECTRICAL MACHINES

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The paper discusses the current developments in the recycling of electrical machines. The main attention is devoted to three types of motors: synchronous reluctance motor, permanent magnet assisted synchronous reluctance motor, and induction motor. Base materials of such electrical machines are also described in the paper. Rare-earth permanent magnets used in electrical machines are review separately. Moreover, the paper considers the features of the disassembly and recycling options.

***Keywords:*** *electric machines, induction motors, permanent magnet motors, recycling*

## 1. INTRODUCTION

Nowadays a lot of attention is devoted to the issues of global warming and climate change. Human activities have caused noticeable effects on the environment from the perspective of resource life cycles, starting from resource consumption and pollution produced up to waste product and recycling. Waste of electrical and electronic equipment such as computers, TV-sets, fridges and cell phones is one of the fastest growing waste streams in the Europe Union (EU), with some 9 million tonnes generated in 2005, and expected to grow to more than 12 million tonnes by 2020 [1]. The economic instruments adopted by the EU to promote waste disposal and disposal fees were consolidated in the EU's 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 [2]. It is estimated that more than 53 % of the electricity consumed globally is used in electric motor systems in industry, buildings, agriculture and transport [3], which means about 6040 Mt of $CO_2$ emissions per year [4]. As part of the coordinated efforts throughout the world to reduce $CO_2$ emissions and energy consumption the regulation authorities in many EU countries have introduced the ICE 60034-30-1:2014 regulation to stimulate the production and use of high-efficiency motors [5]. Today there are four energy classes of electric motors:

- IE1 Standard efficiency;
- IE2 High efficiency;
- IE3 Premium efficiency;
- IE4 Super premium efficiency.

Energy efficiency requirements lead researchers to develop alternative technologies for electric motors. One possibility to reach the IE3 and IE4 efficiency class is to use rare-earth permanent magnets (PM) in the electric motors, which in the end may lead to higher environmental footprint compared to IE2 efficiency class motors.

The present research continues previous studies on lifecycle analyses of different electric motors [6], [7].

## 2. MATERIALS IN ELECTRICAL MACHINES

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

Mostly, windings of electrical machines are made of copper but also other materials can be used such as aluminium in case of squirrel cage induction machines, rotor winding are often made of aluminium. Copper is around three times more expensive than aluminium, but its conductivity is 1.6 times higher, 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, small hysteresis losses and high permeability. Laminations are separated from each other with the varnish of insulation. Electrical steel is an iron alloy to which silicon is added. Silicon is added to the material as it reduces the conductivity of the material resulting in lower Eddy current losses and narrows the hysteresis loop resulting in lower hysteresis losses. The amount of silicon added to the alloy in a commercial product is usually up to 3.2 % as higher concentrations may provoke brittleness during the cold rolling [8]. Electrical steel used in electrical machines is grain non-oriented and the one used in transformers is grain oriented.

One alternative to the electrical steel laminations is the use of Soft Magnetic Composites (SMC) that can be described as ferromagnetic powder particles surrounded by an electrical insulating film [9]. SMC provide good relative permeability, magnetic saturation and high electrical resistivity. The size of the particles is typically 5–200 μm, to be compared with the thickness of laminations, which is normally 200–1000 μm [10]. SMC offer 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, i.e., it is possible to lead the flux in three-dimensions. SMC have several advantages, such as reduction in weight and size. On the other hand, SMC materials are characterised by high core losses compared to 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 most appropriate for use 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 [10].

Rolling bearings used in electric machines 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 should be hardwearing that means the materials should match specific requirements for strength and dimensions. Materials for bearing production depend on electrical machine size and design, as well as on operation properties such as speed and environment. Metal bearings are usually made of chrome steel, stainless steel or carbon alloy steel. Some manufactures provide electrically insulated bearings to prevent current from passing through the bearing. Such bearings could be made of plastic for low power or of ceramics for high power electrical machines. These bearings can improve reliability and increase machine uptime by virtually eliminating the problem of electrical erosion.

For shaft production most manufacturers of electrical machines use carbon steel SAE 1045 (cold-rolled or hot-rolled). SAE 1045 is a medium carbon, medium tensile steel supplied as forged or normalized. 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 SAE 1117, SAE 1137, SAE 1144, hot-rolled SAE 1035, and cold-rolled SAE 1018.

Stator of the electrical machine is fixed to a frame and a rotor, that is arranged to rotate around its axis, supported to the frame by rolling bearings. Usually frame of the electrical machine is equipped with cooling ribs for passive cooling or build-in liquid cooling system for active cooling. Frame of the electrical machine is usually made of non-ferrous aluminium alloy; previously cast iron alloys were also used.

Using PM in electrical machines presents an opportunity to build energy efficient machines. There are three classes of PMs currently used for electric motors:

- Alnicos (Al, Ni, Co, Fe);
- Ceramics (ferrites), i.e., barium ferrite $BaOx6Fe2O_3$ and strontium ferrite SrOx6Fe2O3;
- Rare-earth materials, i.e., SmCo (Samarium-Cobalt) and NdFeB (Neodymium-Iron-Boron).

Figure 1 presents the B-H curves for different types of PM. The remanence and coercivity of NdFeB is higher than of another type of PM. Despite substantial advantages, neodymium (Nd) magnets have a relative low Curie temperature, which is a huge disadvantage in comparison with another type of magnets. However, adding another rare-earth element, such as dysprosium (Dy) helps increase maximum temperature range that is important for use in electric motors. Adding of the small amount of Dy leads to a significant increase in magnet costs, because Dy is rarer and 7 times expensive than Nd [11].

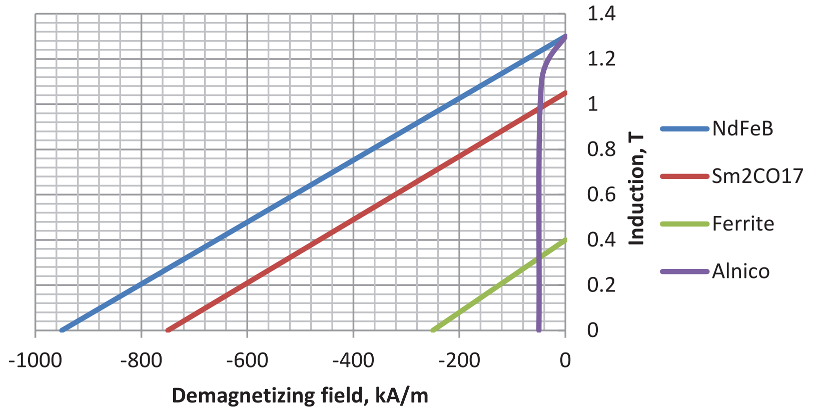


*Fig. 1*. Demagnetization curves for different permanent magnet materials.

Magnets made of rare earth elements have given a push forward in the development of PM. SmCo magnets usually are too expensive to be used in electrical machines. At the same time, NdFeB magnets are more favourable than SmCo magnets regarding energy density, but their long-term problem has been their endurance of heat. However, in the past decade NdFeB magnets have greatly evolved in their endurance capability to heat and corrosion. This makes them one of the most commonly used magnetic materials in large electrical machines. Consumption of rare earth elements has been rising due to their usage in wind generators and lately also in electric vehicle drives. However, the supply with present consumption should be available for more than 1000 years.

The number of materials used in the machines depends on the machine ratings and the types of the machines. The different types of machines can be compared based on the percentage values of the materials used. For example, the percentage ratio of raw materials used for 10kW motors [7] is presented in Fig. 2. For comparison purposes, three types of machines have been chosen: synchronous reluctance motor (SynRM), permanent magnet assisted synchronous reluctance motor (PMSynRM) and induction motor (IM). It can be seen in Fig. 2 that the main material used in the machines is electrical steel, followed by aluminium that is used for machine frame. The third most popular material is insulation materials, such as winding insulation, impregnation resin, paint, packing material, etc. Then copper and finally other materials and permanent magnets are used.

The stator part of all three presented motors is exactly the same; the main difference in construction and materials comes from the rotor part. The rotor winding of IM consists of parallel conductors and end rings, which are welded or 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 magnetic poles through magnetic reluctance. In PMSynRM, the projections are filled with PM bars.

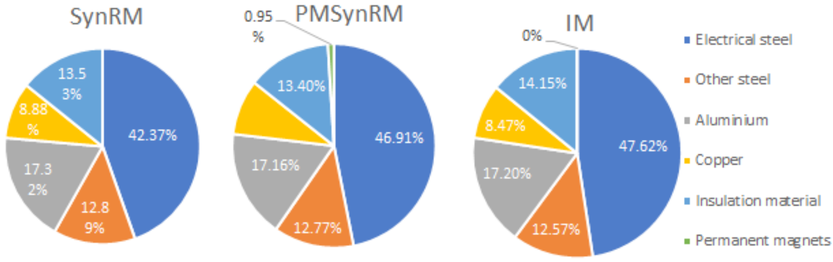


*Fig. 2*. Percentage ratio of raw materials used for production of different 10kW motors.

## 3. RECYCLING METHODS

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

Today recycling of small power electrical machines is based on shredding. During the shredding procedure, electrical machines are cut into small pieces and sorted automatically or manually. There is also a risk that different materials in a product will be mixed in the shredding procedure and therefore not properly separated [12]. Nonferrous metals can be detached from iron materials by magnetic separation, but even small mixing of materials gives a 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 good quality iron the copper content has to be lower than 0.02 % [10].

More powerful electrical machines that are too big for shredding and can damage the grind they are handled separately [13]. Disassembly of powerful electrical machines can be performed by using robotics (automatic), manually or combined. Difficulty of automatic disassembly lies in the deformed shape of some electrical machines, at the same time manual disassembling leads to high labour costs. As the studies show [14], best results of disassembling can be reached by using the optimization models constructed by prioritization of the components and the materials in the product. Separate parts of disassembled electrical machines can be reused in case they do not have any damage and are not worn out.

Disassembling technique is highly dependent on 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 could 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 [15]. After disassembling and, if necessary, demagnetization, PM can theoretically be processed in a recycling plant. At present, the recycling of NdFeB magnets does not exist outside China [16] where mainly production waste is 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 [17]. Some other recycling methods for rare earth PM are the following: reprocessing of alloys to magnets after hydrogen decrepitating, hydrometallurgical methods, pyrometallurgical methods or gas-phase extraction [15].

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 [18]. The bearing industry uses different materials for the production of various bearing components; these materials are processed to achieve desirable properties to maximise bearing performance and life. Due to the friction wear, the rolling bearing could not be reused directly, and remelting is the only way to recycle rolling bearings.

The main parameter of electrical machine winding is the quality of insulation. Lifecycle of insulation is usually around 25–30 years, it is very sensitive to temperature changing and exposed to aging. That is why the copper windings of electrical machines are always remelted after disassembling.

Some researchers present modular construction of electrical machines [19], [20]. The main benefit of such modular construction is that electrical machines can be easily dissembled and damaged parts may be replaced or healthy parts can be separately reused in other electrical machines of that type. Moreover, there are some solutions for direct reuse of rare-earth PM [21] that offer re-using small, unit-cell (segmented) magnets to replace the normal solid pole configuration. The scope of cost aspect evaluation in the research is shown in Fig. 3.

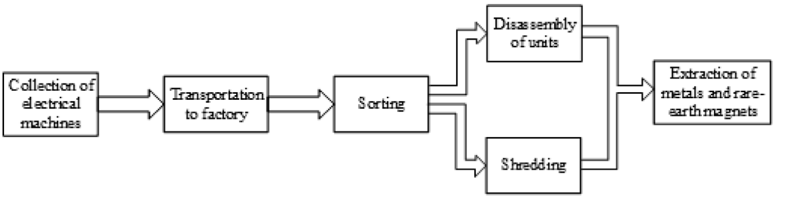


*Fig. 3*. Evaluation of recycling costs of electrical machines for end-of-life product extraction.

Recycling of electrical machines from end-of-life products comprises the following steps:

- the collection process for disposed end-of-life products;
- the process of transporting the removed units to the disassembly location, 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 of extracting metals and rare-earths (NdFeB) from rare-earth components.

## 4. COST ASPECTS AND ENVIRONMENTAL IMPACT

In 2018, cost of material is estimated to be 0.57 €/kg for iron ore, 5.5 €/kg for copper, 1.7 €/kg for aluminium and 2.3 €/kg for electrical steel in rolls. Price of Nd has been unsteadying during the past decade; it has started to grow during the past decade. In 2011, Nd price made a sharp leap and grew almost twenty-five times but decreased to the same price as a decade ago. In 2018, the cost of Nd metal is estimated to be 49.5 €/kg. China is one of the main producers of rare earth elements and also the main policymaker of Nd price. However, building new mines outside China has already started, which should stabilise the market and make rare earth materials more available for consumers; proper exploitation of those mines could take years.

Figure 4 shows a percentage ratio of raw material price based on the production of different 10 kW motors. If the price of IM raw materials is 100 %, the price for producing IM and SynRM is almost equal (100 % and 98 %, respectively), but considering the price of PM the same price for PMSynRM will be 118 %.

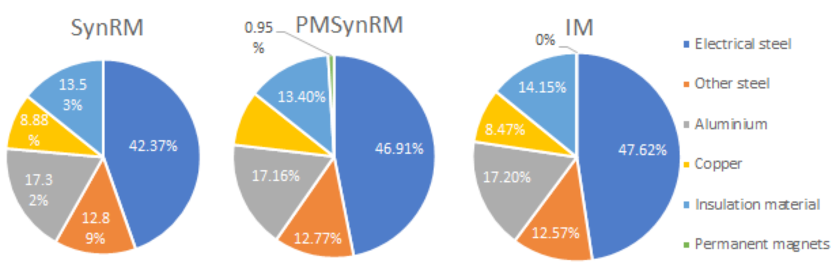


*Fig. 4*. Percentage ratio of raw material price based on the production of different 10kW motors.

The worst case, if the electrical machine is not recycled then it poses the considerable impact on the environment. Depending on a recycling method, electrical steel can be more environmentally-friendly, but has higher labour cost by direct reuse, or has higher environmental impact and more economical profit by shredding. It is worth noting that electrical steel is an alloy with very specific properties. Any kind of reuse of electrical steel, except direct reuse, is affecting material properties and it could not 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 determine the electromagnetic properties [22]”id” : “ITEM-1”, “issue” : “5”, “issued” : { “date-parts” : [ [ “2016”, “5” ] ] }, “page” : “1-4”, “title” : “Effect of the Interdependence of Cold Rolling Strategies and Subsequent Punching on Magnetic Properties of NO Steel Sheets”, “type” : “article-journal”, “volume” : “52” }, “uris” : [ “http://www.mendeley.com/documents/?uuid=4a30dcdc-c0cd-3ac1-a4e2-ce88b75eacbd” ] } ], “mendeley” : { “formattedCitation” : “[22]”, “plainTextFormattedCitation” : “[22]”, “previouslyFormattedCitation” : “(Steentjes et al. 2016. Copper and aluminium that are used for winding could not be reused directly due to insulation of conductive parts of electrical machine. The only one solution is remelting, but in this case the remelted copper/aluminium will contain impurities that will decrease the quality of raw material. In this case, economical profit highly depends on melting and processing energy costs and labour cost; moreover, material losses should be considered. The only way to reuse non-electrical steel in electrical machines is melting, while during the usage phase the parts made of iron are usually wearing out (shaft, frame, bearings, etc.) In this case, steel alloys lost their features and after recycling raw steel should be processed once again (e.g., hardening), resulting in higher environmental impact. Nowadays, environmental impact of PM is not taken into account very much. Environmental impact could be decreased by using some advanced recycling methods.

There is less research made on environmental impacts of electrical machine during the end of the life. For example, in [23]the suitable industrial tools for mass production and a transportation system able to bring each motor to its right place. During the use phase, the motor losses correspond to extra energy consumption and the corresponding environmental impacts for a given local electricity production system. End-of-life scenario corresponds also to extra pollution. During each phase, greenhouse gas and other pollutants specific to the manufacture of electrical machine are emitted. Therefore the improvement of the global quality of electrical machines needs a comprehensive analysis of the environmental impact. This study applies the life cycle assessment (LCA for 10 kW IM it is considered that aluminium, copper and steel are recycled, respectively, to 70 %, 70 % and 45 % and the remaining waste is incinerated and buried at a rate equal to 53 % and 47%, respectively. Recovery amount of metals and rare-earth magnets is an important factor in the appraisal of recycling costs. Thus, we first should estimate the costs of the recycling and then compare it to the amount of products obtained from the electrical machines.

The total costs can be estimated by accumulating the labour cost, the utility cost, the depreciation cost for the recycling equipment, the purchase cost for the used products, and the gain on sale of recovered metals and rare-earth magnets. The labour and utility costs can be obtained from disassembly test.

The recycling costs are given by equation (1):

$$G_{total} = \sum_{i=1}^{5} g_i, \tag{1}$$

where $G_{total}$ – is the total cost of recycling and includes costs of all the particular recycling steps according to steps described in Fig. 3. For instance, $g_1$ -includes cost of the used electrical machines, $g_2$ – transportation costs, $g_3$ – manual sorting of the machines according to their type, power range and dimensions, $g_4$ – costs of shredding or dissembling based on the motor type and its design, $g_5$ – the cost of extraction of final products with the help of manual and automated processes.

## 5. CONCLUSION

The present paper has summarised the recent developments regarding the key components of electrical machine, which are windings, stator and rotor cores, bearings, frame, shaft and possibly PM.

SynRM and IM do not have any rare-earth elements and can be shredded. Different materials in a product will be mixed during the shredding procedure, although nonferrous metals could be detached using magnetic separation. PMSynRM contains relatively high concentrations of valuable compounds such as PM magnets that suffer from poor recycling efficiencies during shredding, which means disassembling will be the main recycling method for such electrical machines.

Raw materials obtained during recycling can be reused directly, remelted into different alloy or used in powder metallurgy for further production. The steps described in the paper are designed to increase efficiency of material reuse in order to achieve low recycling cost and high recycling rates. Problems of the electrical machine recycling with modern technologies based on the contemporary social systems are clarified, and the starting point of the research problem is identified.

Meanwhile, we have made a number of assumptions that must be specified in future research to develop a more comprehensive understanding of the accurate cost estimation for electrical machine recycling industry in different countries. We have assumed that the entire recycle chain consists of particular steps but we should take into account that the cost of each step varies and depends on many variables, such as price of the electrical energy, fuel, labour costs, governmental regulations and other factors.

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DAŽĀDU ELEKTRISKO MAŠĪNU ATKĀRTOTA IZMANTOŠANA UN PĀRSTRĀDE

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T. Vaimann, A. Belahcen.

K o p s a v i l k u m s

Šajā rakstā aplūkotas pašreizējās pārmaiņas elektrisko mašīnu pārstrādē. Galvenā uzmanība tiek vērsta trim dzinēju tipiem: sinhronais pārslēdzamais dzinējs, sinhronais pārslēdzamais dzinējs ar pastāvīgiem magnētiem un asinhronais dzinējs. Tiek aprakstītas šo mašīnu galvenie materiāli. Atsevišķi tiek apskatīti retzemju pastāvīgie magnēti. Turklāt tiek apspriestas izjaukšanas un pārstrādes iespējas.

01.06.2018.