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Identification for Remanufacturing of a Synchronous Reluctance Machine Considering the Circular Economy Conditions

Mihály Katona, Miklós Kuczmann, Tamás Orosz*

Department of Power Electronics and Electric Drives. Széchenyi István University, 1. Egyetem tér, Győr HU-9026
orosz.tamas@sze.hu

Due to the growing pressure from governmental entities and customers in the European Union, Original Equipment Manufacturers are being pushed to design and manufacture sustainable and environmentally friendly products. A profitable industrial segment is expected to emerge from recycling end-of-life electric machines. This paper aims to identify an experimental synchronous reluctance machine with faulty copper windings to remanufacture the machine. The rewound design aims to achieve similar or improved characteristics and fit the novel requirements of the circular economy. The recyclability of the machine can be significantly increased by changing the copper windings to aluminum-based hairpin windings. The paper shows the geometrical, material, and winding identification plus finite element method-based analysis of the initial machine. The electric machine’s slot-filling factor can be improved using an appropriate aluminum-based hairpin winding design compared to the original, even in the case of standard slots where the sides of the slots are not parallel.

1. Introduction

The European Commission released the new circular economy action plan to ensure the European Union's (EU) transition from the linear economy model to the circular economy model (European Commission, 2020). With the action plan, the European Commission aims to regulate and widen the following aspects of the circular economy model, highlighting the points relevant to this research: improving product energy efficiency and resource efficiency, enabling remanufacturing, and reducing carbon- and environmental footprints. Besides the regulatory pressure, companies aim to make their manufacturing processes more sustainable as Vig et al. (2022) reported about the company Tesla. The methodology used to investigate the environmental footprint is called Life Cycle Assessment (LCA), which has been recently expanded to the Circular Economy - Life Cycle Assessment (CE-LCA) framework (Ngan et al., 2021). A study by Cambridge Econometrics and ICF (2018) estimates that the transition may increase the EU's Gross Domestic Product (GDP) by an additional 0.5 % by 2030, creating around 700,000 new jobs. Additionally, it may offer "600 billion Euros in savings", a 30 % increase in resource productivity, and a reduction in greenhouse gas emissions (Kalmykova et al., 2018). The circular economy concept started to gain attention in the last decade, covering reducing, reusing, and recycling activities (Kirchherr et al., 2017).

In the case of electric machines, the circular economy concept is about the process of reuse, refurbishment, remanufacturing, and recycling. Remanufacturing is a life extension strategy for an electric machine at its end-of-life. An electric machine may reach its end-of-life at the end of its lifetime as intended or because of unforeseen faults. Remanufacturing means complete disassembly of the electric machine and recovery at a component level (Tiwari et al., 2021). After disassembling the low-efficiency and faulty electric machine by reusing the original machine's usable components and replacing the bearings, windings, and rotor by using recent or advanced manufacturing technologies, a high-efficiency remanufacturing of the electric machine can be realized (Li et al., 2021).

Li et al. (2021) recently published the process of remanufacturing an asynchronous machine to a permanent magnet synchronous machine under circular economy conditions. The study's motivation is to remanufacture an outdated, high-power (110 kW) industrial electric machine into a high-efficiency one. In the case of high-

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power applications, restoring the machine costs less than a new product while minimizing the environmental impact of the manufacturing process. The treatment is divided into destructive processes, where the component is no longer reusable as initially intended, and non-destructive processes, where the component is reusable in the remanufactured electric machine. The advantages of remanufactured electric machines are that they are cheaper than a new product, there is no need for a new frame where the machine is utilized, and the energy savings are higher than initially.

In the case of rewinding, the most advanced winding technology is the hairpin winding. The advantages of this technology are the high slot fill factor, excellent heat dissipation, strong rigidity, short end-windings, and that it can be manufactured automatically. Randomly positioned, round wires fill the stator slots less efficiently; those will never match their shape. On the other hand, form-wound conductors such as hairpin winding can fill the slot better if the sides of the slots are parallel. This way, the direct current (DC) losses of the machine are reduced, but the disadvantage of this type of winding is the higher alternating current (AC) power loss at high frequencies (Soltani et al., 2021).

The political and consumer demand for sustainable electrification of transportation has moved the industry in a direction that makes it reconsider aluminum winding. The advantages of aluminum winding are that it is lightweight, flexible, and cheaper than copper, but its conductivity is also lower (Petrelli et al., 2022). From the sustainability point of view, the weighting factors of Environmental Priority Strategies (IVL, 2020) is a possible numerical comparison of aluminum and copper. It defines Environmental Load Units (ELU), indicating the cost of environmental impact using natural resources. Copper has an ELU of 131, while aluminum has only 0.16. Acquaviva et al. (2021) found that in the case of e-mobility applications, aluminum hairpin winding has comparable efficiency to copper hairpin winding, considering the same electric motor topology and the same current density.

The circular economy concept has been criticized by Corvellec et al. (2022) for its unclear implementation and lack of published methodologies for identifying which electric machines are suitable for remanufacturing at the end of life. While Li et al. (2022) analyzed the recycling and remanufacturing technology of a permanent magnet synchronous motor, the authors did not address the identification process of the electric machine. This paper presents a reverse engineering process of an experimental synchronous reluctance machine to address this gap. The process includes the identification of the geometry and the winding scheme, which is essential for remanufacturing. This approach involves replacing faulty copper windings with enameled round wires to aluminum hairpin windings and calculating the difference in the slot-filling factors. This study provides a showcase of the challenges of remanufacturing electric machines and contributes to the realization of a circular economy. The paper is divided into three parts, with section 2 presenting the reverse engineering process and methods. Section 3 provides a summary of the results.

2. Methods - Identification of the electric machine

There are two similar synchronous reluctance machines in the Department of Power Electronics and Electric Drives' laboratory at Széchenyi István University. One of the motors has a faulty winding that serves as a basis for the destructive remanufacturing process and identification.

2.1 Geometry

The geometry of the stator is based on the machine's blueprint, which is publicly available (Katona, 2023). According to the control measurement of the stator iron core geometry, the blueprint contains the appropriate dimensions. The same cannot be stated for the geometry of the rotor. There is a clear difference in rotor geometry between the blueprint and the realized laminate. The blueprint does not contain all the dimensions of the rotor geometry. In Figure 1. the 2D geometry of the investigated electric machine is presented. One laminate was removed from the shaft and scanned with a high-resolution scanner to identify the rotor topology and dimension. The scanned image provided the basis for the 2D vectorized drawing created in Autodesk AutoCAD supplemented by manual measurements.

2.2 Material characteristics

In the blueprints, the steel from which the electric machine was built is designated by S235. The S235 steel is a non-alloy carbon structural steel grade divided into different quality grades by the EN 10025 and EN 10210 standards. The S235 steel is not defined as an electrical steel as it does not contain any silicon. The primary application of S235 is for structural components, and some researchers tried to use this material for electrical brakes. It was found that the A36 structural steel approximates the electromagnetic properties of S235-grade steel. Aragon-Verduzco et al. (2019) investigated the electromagnetic properties of A36-grade steel by the Epstein frame method to increase the precision of electromagnetic loss calculation in transformers. In this paper, the iron core material is specified by the measurement results of Aragon-Verduzco et al. (2019) at 25-70 °C.

2.3 Winding

The ohmic resistance measurement of the copper winding showed a significant difference in the phase resistances: phase U: 37.2 mΩ, phase V: 18.9 mΩ, and phase W: 32.6 mΩ. This difference indicated that there was a short circuit or faulty soldering. The measurement results prompted a need for rewinding of the machine. Identifying the winding scheme is crucial for the simulations to be precise enough and to create a baseline for improvements. The stator has 48 slots, and the machine has three phases and four poles. Following the rules of winding symmetry shown in Eq(1), the number of slots per pole and phase is four.

$$q = Z/(2pm) \tag{1}$$

The winding heads were used as a basis for the identification as the winding on one side has been removed by retaining its original condition. Identifying the copper wire used for winding is a must to determine the slot-filling factor. It is assumed that the wire is manufactured according to the IEC 60317-0-1 international standard (IEC, 2019). The grade denotes the degree of thickness of the insulation of a wire, and the enameled means a wire coated with insulation of cured resin. For winding electrical machines, generators, and transformers, the polyester or polyesterimide overcoated with polyamide-imide enameled round copper wire of class 200 with a dual coating is generally used and standardized in the IEC 60317-13 international standard (IEC, 2010). Class 200 is a thermal class that requires a minimum temperature index of 200, meaning 20,000 h of guaranteed service life at 200 °C (IEC, 2020). It was assumed that the investigated electric machine's winding is as defined by international standards. The material was defined in Finite Element Method Magnetics (FEMM) software with a conductivity of 58 MS/m based on Vajsz et al. (2022).

2.4 Finite Element Analysis

The Digital-Twin-Distiller python package was used with the finite element solver FEMM to automate the simulations that are fully available in (Katona, 2023). The simulations represent the torque capability measurement precisely as written in (Hsu et al., 2004). In the magneto-static setup, the phase current density was calculated from Eq(2), where i_0 = 25 A, A_s = 142.793 mm^2, k = U, V, W and j = 0, 1, 2. The excitation is fixed during the whole simulation, representing the DC supply. The torque was calculated in different rotor positions as 0° to 90° in mechanical degrees with the steps 0.25°.

$$J_k = \frac{N * i_0}{A_s} * \cos(j * 120°) \tag{2}$$

2.5 Slot-filling factor of the winding

The slot-filling factor is the ratio between the cross-sectional area of all conductors in one slot and the entire slot area. Generally, in electric machines with standard slots, where the sides of the slots are not parallel, the filling factor is between 0.4 and 0.6. For insulated conductors with the same cross-section area, the filling factor is always higher for rectangular conductors than for round conductors (Di Tommaso et al., 2017). A higher slot-filling factor means a higher cross-sectional area, reducing the current density and the phase resistance, resulting in lower copper losses (Kulan et al., 2016). The current density is calculated by Eq(3). The maximal current density per turn is limited at 4 A/mm^2 as no active cooling is attached to the machine. The insulation thickness of the round wires is assumed to be 0.3 mm, and the insulation around the sides of the slot is 0.2 mm.

$$J_{cn} = \frac{i_0}{\left(\frac{d}{2}\right)^2 \pi * n * N} \tag{3}$$

3. Results

The identification of the geometry resulted in a 2D model of the machine for Finite Element Analysis, presented in Figure 1. The stator consists of 48 slots; it has an inner diameter of 170 mm, an outer diameter of 240 mm, and a stack length of 70 mm. The stack length of the rotor is 78 mm, 8 mm longer than the stator. It was found that the rotor is a Machaon-type structure, meaning an asymmetric rotor where the flux barriers of the adjacent poles are different. Castagnaro and Bianchi (2019) compared two synchronous reluctance machines by symmetric and Machaon flux barriers regarding noise, vibration and harshness. It was found that the Machaon-type machine has a lower mean torque value by 5 %, lower torque ripple and lower vibration by 50 dB in the considered frequency range. The geometry is available at (Katona, 2023).

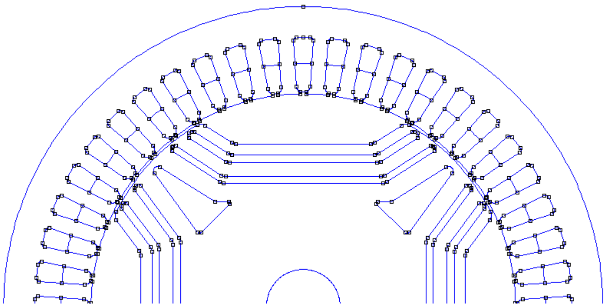

Figure 1: The 2D geometry of the investigated electric machine

Identifying the copper wire used for winding is a must to determine the slot-filling factor. The measurement results of the wire diameter fell in the range of 0.69 – 0.71 mm. Assuming that the wire is manufactured according to the IEC 60317-0-1 international standard (IEC, 2019), the results match the 0.675 mm – 0.749 mm range of an enameled copper wire with 0.67 mm nominal conductor diameter. One turn has n= 20 enameled round copper wires, and one slot contains N = 8 turns, meaning 160 wires per slot. There is no winding pitch based on the winding heads, so one phase fills a whole slot. The winding scheme of phase U drawn based on the inspection of the winding heads is shown in Figure 2. By examining the manually removed winding, it was found that it is distributed.

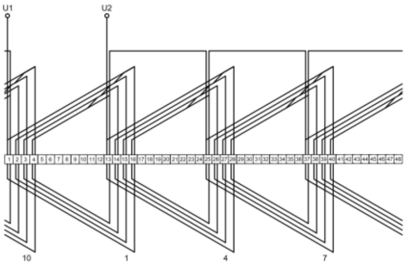

Figure 2: Winding scheme of phase U drawn based on the inspection of the winding heads

The simulated torque capability and the flux density distribution at 25 A is shown in Figure 3. There is an imbalance in the saturation of the stator yoke and the rotor flux barrier. The uncertainties of the simulation are the uncertainty of the S235 steel's B-H curve or the uncertainties of the rotor dimensions. It was shown by Katona et al. (2023) that minor geometrical changes in the manufacturing tolerance range could change the torque output of the electric machines if not designed in a robust way.

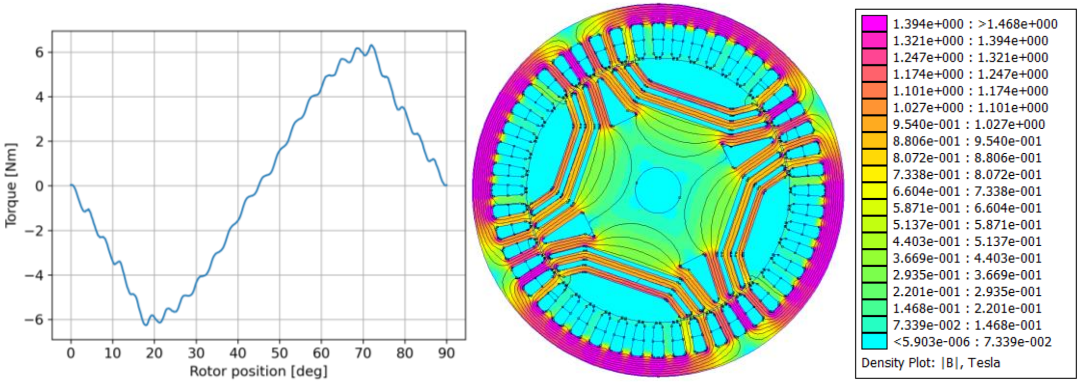

Figure 3: Simulation results of the torque capabilities at the axial length of the stator L = 70 mm

The current density of one copper wire is J_{c1} = 0.443 A/mm^2, which means J_{c20} = 8.863 A/mm^2 for one turn, calculated by Eq(3). The current density is higher than the previously set 4 A/mm^2 limit, which indicates that the machine was designed for operation with active cooling. The cross-sectional area of the slot is A_s = 142.793 mm^2. Still, the cross-sectional area of the enameled round copper wires' conducting part is around A_r = 56.410

mm^2, meaning a slot-filling factor (f_r) of 0.395. Figure 4a. presents the 160 round wires in an ideal arrangement. In Figure 4b. using rectangular wires, the conducting cross-sectional area can be increased to A_f = 75.98 mm^2 and the filling factor to f_f= 0.532 instead of f_r = 0.395.

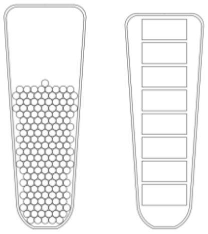

Figure 4: Comparison of round and rectangular wires: a) (left) ideal arrangement of 160 round wires; b) (right) rectangular wires with N = 8

4. Conclusion

There is a lack of published methodologies or practical implementations for identifying electric machines suitable for remanufacturing at the machine's end-of-life. The paper focuses on addressing this issue by identifying an experimental synchronous reluctance machine and highlighting the uncertainties that are present in terms of the machine's geometry, material characteristics, and winding scheme, which contributes to the realization of a circular economy. The faulty winding of the machine prompted the need for investigation of rewinding. The study showed that even in standard slots, where the sides of the slots are not parallel, using rectangular wires, it is possible to increase the slot-filling factor by 0.137 compared to the original design. This increase in slot-filling factor is expected to enable the aluminum-based hairpin winding to compete with the enameled round copper winding.

Nomenclature

q – the number of slots per pole and phase, -
Z – number of slots, -
p – number of poles, -
m – number of phases, -
n – number of wires per turn, -
N – number of turns per slot, -

i_0 – current, A
J_U, J_V, J_W – current density, A/mm^2
A – cross-sectional area, mm^2
f – slot-filling factor

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