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Non destructive control of permanent magnet rotors in a perspective of electric motor circularity

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Abstract

This work presents an innovative non destructive control process in order to guide for the end of life (re-use or recycling) of permanents magnets (PM) rotors of electric motors. The process is based on the measurement of the external field produced by the PM rotors. A Finite Element model of the rotor and its environment has been used to simulate a process of classification of the geometry of PM rotors, crucial information for the disassembling of the PM. Firstly, using a finite element model, we were able to investigate the field distribution outside the rotor of the magnetic flux density for different PM rotors designs. From this information, we can set up a classification methodology, based on the Central Voronoi Tessellation (CVT) method, which can help to identify how the PM are inserted within the rotor. This information can be very useful to choose PM disassembling process that should be applied.

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Keywords: Recycling, Electrical Machines, Permanent Magnet Rotors, classification, magnetic field

1. Introduction

This paper presents a new non-destructive identification technic developed to face the needs of increasing circular economy of electric motor and the permanent magnets. The environmental transition shifts to a more electric world. Electric motors (e-motors) are a key technology for this transition. In the case of the electric vehicles, they are today more and more used in the automotive industry. The production of the electric vehicles and electric machines is increasing. These machines are mainly synchronous machine using Permanent Magnets (PMs) to magnetize the rotor. In fact, this kind of machines have a high efficiency as well as very high performances in terms of volumic/massic torques. This PMs is based on rare earth elements and other huge value materials (Nd neodyme, Dy dysposium, Sm samarium, Co, Ni, B...) and other that are today listed as critical raw materials. The growing demand of electric machines increases the pressure on these resources. Therefore, the development of effective End of Life strategies for PM is essential to mitigate the environmental impact associated with their production and meet the rising demand sustainably. The reuse or the recycling of rare earth PM has become a crucial issue to make effective circular economy solutions for this type of product and resources. If the rotor is free of defect, it can be reused as it is in another electric machine of the same type; else the PM should be extracted from the rotor to be recycled to fabricate new PMs. The process of extraction will depend on how the PM is positioned in the rotor in order to define how to extract them. This information is not always available when the electric machine is considered for recycling, so it has be determined from experimental tests which should be easy to carry out, not expensive, fast and reliable. Moreover, the quality of the PM, after their use (loss of magnetic power due to its life) or disassembly process, is a key information for the possible 2nd life as magnet or only materials.

Recently several researchers developed fault detection and diagnostic of PM rotors [1, 2]. These studies show that the demagnetization caused by thermal, mechanical or

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environmental stress is the major defect which leads to irreversible degradation of motor efficiency. The demagnetization leads to a decrease in magnetic flux created by the rotor. This decrease directly impacts the efficiency and power output of the system [1, 3]. Thus, methods based on the external magnetic field analysis have been developed [4, 5, 6]. In this paper, we propose to extend the non destructive method based on external field measurement to the determination of the rotor type geometry. Indeed, the field distribution created by the PM depends on the structure of rotor which can be either located on the surface (Surface Mounted PM rotor (SMPM)) or buried inside the rotor structure and surrounded by soft magnetic material like Electrical Steels (Interior Buried PM rotor (IBPM), Flux Barrier PM Rotor (FBPM)). This approach could be very useful to face the absence of comprehensive information about the type and geometry of PM rotors. As these rotors have reached their service life limits, their exact specifications or configurations might not be readily available due to various factors like for example the loss of documentation over time. This information about the geometry of the rotor can be very useful to determine the more efficient route for PM disassembling. In fact, the disassembling process of a SMPM, IBPM or FBPM rotor won't be the same.

In a perspective 2nd life or 2nd use of the PMs, designers will now think on innovative architecture for the electric motors and their rotor. Modular rotors, radial architectures could allow an easier recovery ratio. These efforts are relevant if the 2nd life PMs are still functional with an efficient electromagnetic field. Rotor re-manufacturing becomes a better option than PM recycling. These design efforts rely on the possibility to have identification / characterisation method of end of life e-motors and their magnets. This is also a technic that play a crucial role to guide the decision for only material recycling (then shredding, material separation and sorting) or component recovery (then disassembly of e-motors and rotor).In this paper, we propose a simple methodology based on the external magnetic field measurement in order to classify PM rotors based on their geometry. This classification method is based on based on the Central Voronoi Tessellation (CVT) method. The process of classification is simulated using a Finite Element Model which enables to construct virtual prototypes of the different rotors and to determine the associated external magnetic field distribution.

2. Permanent magnet machine and recycling

2.1 Operating principle

PM synchronous electric machine are today widely used due the fact that they have the advantage of lower weight, higher torque and/or output power, lower maintenance and a simplification of the machine construction [1,7].Moreover, these PM machines have higher efficiency than their field wound rotor counterparts [8].

PM machines as other electric machines are composed mainly of a stator and rotor core, windings, and PM. Moreover, supporting components like bearings, the frame, and the shaft are integral to the machine's overall assembly. The functioning of electrical machines relies heavily on the interaction between magnetic fields created by the PMs located on the rotor and by the supply currents on the stator [9]. Rare-earth PM, specifically NdFeB and SmCo, are the most used in rotor, and have become vital in the construction of PM machines, notably for automotive applications due to their high energy density [10,11]. These magnets are widely used as magnetic field source. They need to produce the required flux for the machine to reach the desired torque.

2.2 Different structure of PM rotors

It exist different ways of assembling the PMs on the rotor. The PM can be mounted of the rotor surface (SMPM) or buried inside the rotor structure (IPM) [12]. For the latter case, the PM can be buried in different ways depending on the requested effect, especially the reluctance effect. The rotor manufacturing and so the PM disassembling depend highly on the rotor geometry that should be known in order to recycle the PM.

2.3 Recycling

Every electric machine undergoes various stages throughout its lifecycle, starting from its design and manufacture, moving through usage and maintenance, and finally arriving at its end of-life. This last stage signifies the point at which the machine has served its intended purpose and can no longer function effectively or efficiently [13]. Upon reaching the end-of-life stage, the disposal of these machines becomes a significant consideration. However, rather than discarding them as waste, we can utilize several end-of-life methods. These methods can be employed to reclaim and valorise as much as possible the components or materials present in these machines, thereby reducing waste and supporting sustainability. The three key recycling processes that can be applied to PMs machines at their end-of-life stage are represented in Fig. 1 [14].

- **Reuse**

Reuse of PM machines is still an emerging field of study due to quality and availability concerns. However, two potential reuse strategies exist: reusing the entire motor, reusing

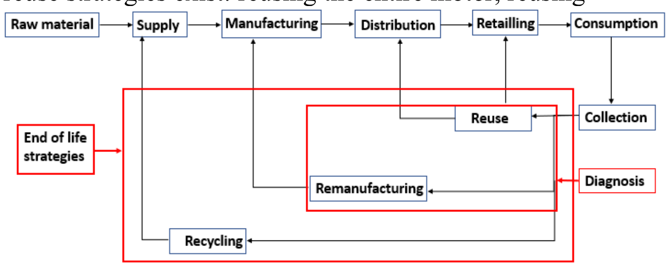

Fig. 1. Life cycle of electrical machines [14].

specific components, as PM rotor, when designing motors for easy disassembly. Reusing PM comes with challenges. Magnets, if undamaged during removal, can be directly reused. Three methods for magnet reuse are: reusing the entire magnet, reusing segmented magnet parts, and reusing magnet powder. Each of these provides varying adaptability depending on the specific application's requirements [15].

- **Remanufacturing**

Remanufacturing is redesigning or replacing components of PM machines, which align with green development goals in the manufacturing sector. It is close to refurbishing, where PM machines are updated to deliver performance and quality equivalent to new ones, complete with warranties and support [16].

Despite its advantages, including cost savings, increased energy efficiency, environmental friendliness, improved quality, and reduced production downtime, remanufacturing is not universally applied due to design differences of electric machines on the market which comes from no really existing standards. Therefore, establishing detailed remanufacturing schemes is critical to promote this practice at the end-of-life stage of electrical machines. The remanufacturing process typically involves retaining the rotor and stator core, replacing or extending windings, or adjusting the winding parameters [17].

- **Recycling**

Recycling PM machines is divided in two main strategies: shredding or disassembly, largely determined by the machine's size. Smaller machines generally undergo shredding, a process that involves reducing the machine into tiny pieces, which are then sorted. However, this method runs the risk of mixing materials, which can lower the quality of recycled output. Certain measures like automated systems can assist in pre-sorting to minimize this issue. On the other hand, large machines necessitate disassembly due to their size and complexity, but also the intrinsic value of the component inside. This process, which can be carried out manually, automatically, or using a hybrid approach, entails carefully taking apart the machine. Post disassembly, components are shredded and remitted, ready for reuse. Special materials, such as undamaged PMs, are singled out for extraction and subsequent reuse. Despite some challenges associated with each method, such as the complex shape of some machines complicating automatic disassembly, these processes allow for effective recycling of PM machines [14]. However, the process of extraction the PMs depends on the rotor geometry which should be known a priori. This information should be determined by measuring the external magnetic field created by the PMs. This process will be detailed in the following.

3. Model and Classification method of permanents magnets

3.1 General methodology

We effectively used a finite element model enabling to calculate the outer field created by the rotor (Octave and FEMM (Finite Element Method Magnetics)) software [18] to design and evaluate five distinctive rotor models. The parameters which greatly influence the performance of the rotor were precisely considered within the finite element models, known for its effectiveness in electromagnetic problem-solving, allowed for precise physical representation of the magnetic field created by the PM rotor.

Upon creating the rotor models, we have employed Octave coupled with the finite element model in order to simulate different rotor structures presented in Fig. 2. The structures are parameterized as we can see in Fig. 2 which enables to evaluate the influence of parameter variation on the proposed method of classification. This allowed us to determine the magnetic flux density created outside the rotor. In Fig. 3, we give the evolution of the magnetic flux density on a circle surrounded the rotor. We can see that the magnetic field distribution differs from a rotor structure to another. According to that statement, we can expect to classify the rotor structure according to the outer magnetic flux density distribution.

3.2 Classification method

After view the variation of the magnetic flux density for different rotor geometries, we now turn our attention to a more complex scenario where the geometry of the rotors is unknown. This represents a real-world condition often encountered when dealing with end-of-life (EOL) rotors. Our aim is to accurately identify and characterize the unknown geometry of these rotors. The ability to identify and classify rotors at their end-of-life stage is of maximum importance, as it directly impacts the efficiency and effectiveness of recycling processes. The classification of rotors helps sort these components based on their material composition and structure. By doing so, it becomes possible to direct each type of rotor to the appropriate recycling route, thereby maximizing the recovery of valuable materials and minimizing waste. Furthermore, an efficient classification process can enhance the overall recycling rates, contributing to the economy and aiding in environmental conservation. Therefore, the process of identifying the unknown geometry of rotors becomes a pivotal point in this research.

Thus, we are used Central Voronoi Tessellation (CVT), which is a geometric technique used to partition space into Voronoi cells based on a set of central points. This method is widely employed in various fields such as computer graphics, image processing, optimization, and spatial analysis. The primary objective of CVT is to divide a given area into regions, with each region representing the space closest to a specific generator or central point [19]. In the context of rotor shape identification, CVT finds utility in creating Voronoi cells that correspond to different rotor shapes and geometries. By analysing the properties of these cells, it can be possible to determine the characteristics of rotors, thereby facilitating the recycling process. The identification of rotor shapes and geometry is a very important step for efficient recycling and the detection of defective magnets [20]. In this study, we utilized the Central Voronoi Tessellation (CVT) algorithm to classify machines based on their magnetic flux density measurements, aiming to facilitate the recycling process. Prior to classification, we conducted simulations of different types of machines with varying rotor shapes and geometry, including SMPM, IPM, T-shape, V-shape and IPM double magnet. By calculating the magnetic flux density around each rotor, we obtained valuable data that reflected the unique characteristics of each machine type. These magnetic flux density measurements were then stored in a matrix, which served as the set of vectors for classification using the CVT algorithm. In the following, we will use the CVT algorithm to analyse of the tangential and/or radial components of the magnetic flux density in order to see if we are able to segregate different geometry of rotors. As mentioned before, by accurately identifying rotor shapes and geometry, we can optimize resource utilization and minimize waste in the recycling process.

4. Results and Discussion

4.1 Description of the structure of the PM electrical machine tested

Using FEM, we were able to model five PM rotors structures used in electric motors, as seen in Fig. 3. In this figure, we can clearly see that, apart from the PM being placed on the surface, or buried in the rotors, they can take different shapes. Therefore, once electric machines reach the end of their life, disassembly techniques must be different.

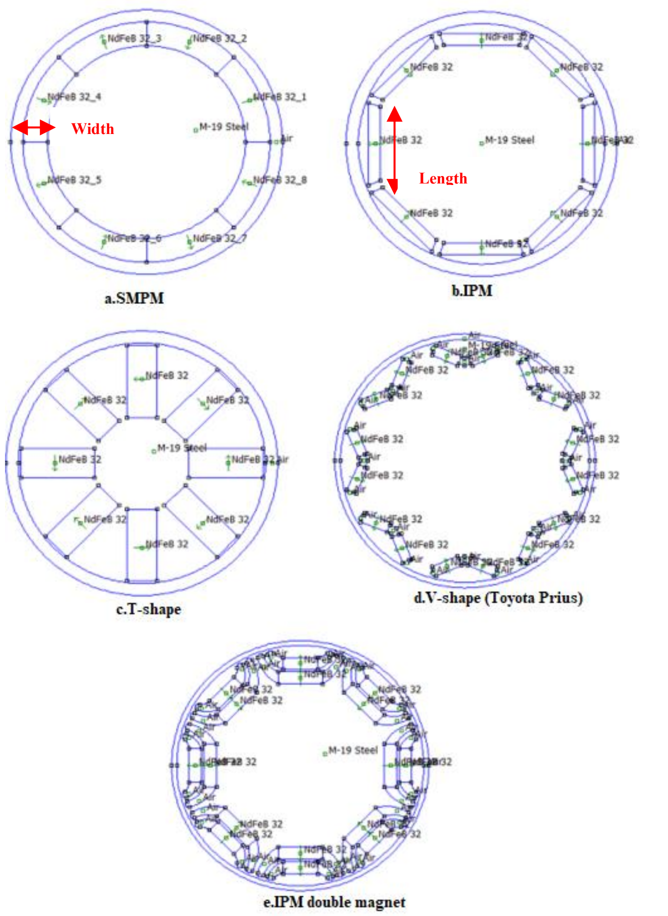

Fig. 2. Models of different shapes of rotors.

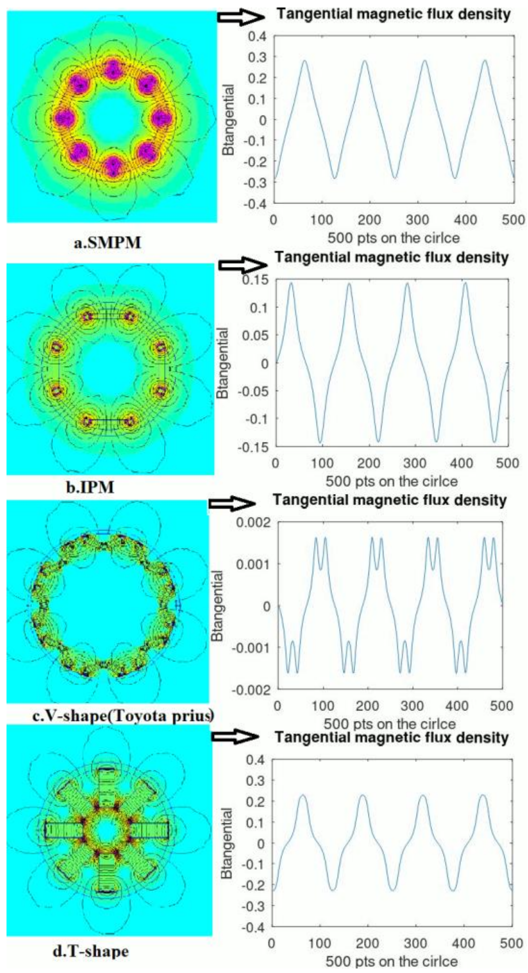

Fig. 3. Field lines distribution and the variation of the magnetic flux density for different rotor geometries.

This is why the use of processes based on rotor geometry becomes interesting. Results of simulation obtaining are presented in Fig. 3. We were able to visualize all the field lines generated by each rotor as well as the magnetic field variation. With these simulations, we can identify the different field distribution created by each geometry and so develop the classification methodology of the different types of PM rotor used in electric machines.

4.2 Results with Central Voronoi Tessellation technic

In the following, we will employ the Central Voronoi Tessellation (CVT) method to classify rotor structures with different parameter values which variation ranges are presented in Table 1.

4.2.1 Trial with the radial flux density

Starting with our initial trials, we use the radial flux density calculated on several (500) points located on a circle close to the source of the rotor. This enable to construct a vector of radial magnetic flux density value which will be used as input for the CVT method.

Table 1: Magnet parameters.

Type of PM rotor	SMPM	IPM	V-Shape (Prius)	T-shape	IPM double magnet
Magnet length (mm)	87	85	7.15	49	40
Magnet width (mm)	50	44	2.55	5	5
Variation step length (mm)				+ 0.1	
Variation step width (mm)	-0.1	-1	+ 0 .03	- 0.163	+ 0.4

Our investigation covers 50 machines, each 10 from 5 different geometries (SMPM, IPM, V-shape, T-shape and IMP double magnet).

These designs were derived by varying both the width and the length of the PM within each rotor configuration. The measured radial field average of the ten rotors is used in the CVT method to classify the 5 types of PM rotors. The results of simulation applying CVT method are illustrated in Fig. 4. Our simulations provide a compelling visual representation with colour-differentiated data points. The star-shaped markers in this figure represent control points, while the colour-filled points are the 50 vectors that we had previously generated. Significantly, this display illustrates the successful application of the Central Voronoi Tessellation (CVT). The space is accurately divided into five distinct categories corresponding each to a rotor structure, demonstrating a highly effective classification process. For a given rotor structure, the 10 points obtained by varying the parameters remain close to each other and far away from the other groups of points corresponding to other rotor structures. The CVT method distinctly classifies all the rotors into their respective categories. Specifically, it showcases the model's ability to differentiate between distinct PM rotor geometries accurately, even when their radial flux density profiles are very close.

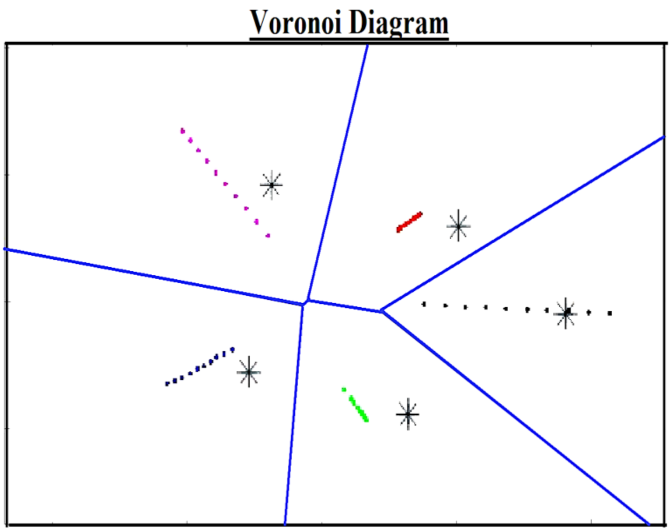

Fig. 4. Voronoi diagram using the radial flux density (red) SMPM, (green) V-Shape, (black) T-Shape, (mauve) IPM and (blue) IMP double magnet.

4.2.2 Trial with the tangential flux density

Building upon our prior discussions, we will now delve into the results derived from analysing the tangential component of the magnetic flux density. For this purpose, we utilized the same values from the finite element model to measure the average value of the tangential field in order to classify the 5 types of rotor. The results obtained are represented in Fig. 5.

This approach presents a distinctively coherent and precise classification of rotor types into four unique categories. A notable aspect of this model is the complete absence of category overlaps, signified by the nonexistence of mixed colors within any single category. This is a strong indication of the absence of any mis-classification. The outcomes of this study reinforce the potential of this approach as a robust tool for classifying PM rotor of electric machines in an effort to streamline recycling processes, promote efficient use of resources, and contribute to environmental sustainability.

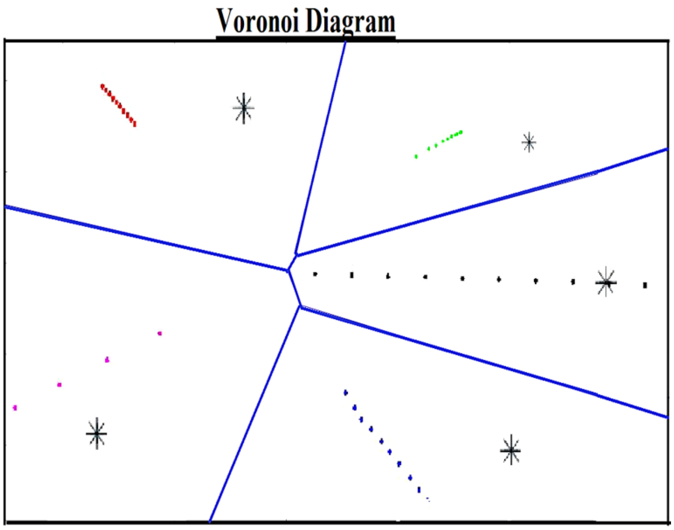

Fig. 5. Voronoi diagram using the tangential flux density.

4.2.3 Trial with disturbance

So that our model is more representative of the of real-world scenarios, we have introduced an element of uncertainty to our analysis. In real-world scenarios, these disturbances can arise from various sources such as environmental factors, including temperature fluctuations, mechanical vibrations and electromagnetic interference. These factors inevitably lead to perturbations in the magnetic flux density measurement, impacting the overall performance and reliability of the machines. Thus, so we redid our simulations by introducing a noise of 5% in the magnetic flux density measurement. The aim was to check if our model would continue to provide accurate results even under these altered circumstances. The results obtained are shown in Fig. 6 where we can observe the effect of the noise which manifests itself by the non-alignment of the different points. As we can see in this figure, the 5 types of PM rotors are still distinctly classified. Our model can classify the machines effectively, even when exposed to noise. This strengthens our methodology and proves its efficacy in real-world scenarios.

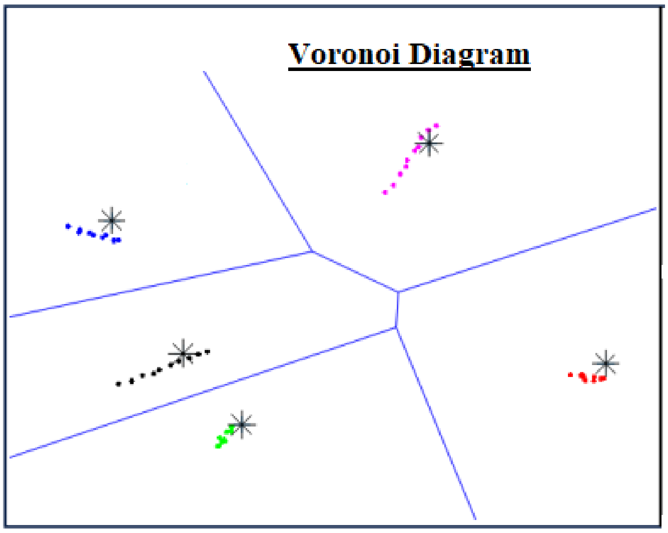

Fig. 6. Voronoi diagram with noise.

5. Conclusion

This paper has presented an approach of classification of the PM rotor geometry based on a non destructive technic consisting in measuring the external magnetic field. The exploitation of the CVT method allows the identifying the geometry of rotors when it's unknown. The process has been simulated using a finite element model and shows clearly that the rotor geometry can be discriminate. The identification of geometry PM rotors, the type of permanent magnet and their magnetic field force, will help the End of Life diagnostic process in order to enhance component (permanent magnet) recovery rather than recycling. If rotor and PM recovery is not relevant, this non destructive characterization can at least help for a better sorting of the PM types, including their materials and rare earth elements inside, to propose a better sorting and then improve the material recycling efficiency. One of the objectives is to reduce both the time and effort traditionally associated with this stage of the recycling process.

References

[1] B. Li, Y. Yuan, P. Gao, Z. Zhang, G. Li. Cooling structure design for an outer-rotor permanent magnet motor based on phase change material. Thermal Science and Engineering Progress 9 July 2022.

[2] Y. Gritli, A. Tani, C. Rossi, D. Casadei. Assessment of current and voltage signature analysis for the diagnosis of rotor magnet demagnetization in five-phase AC permanent magnet generator drives. Mathematics and Computers in Simulation 158 (2019) 91–106.

[3] A. Rassõlkin, A. Kallaste, S. Orlova, L. Gevorkov, T. Vaimann, A. Belahcen. Re-Use and Recycling of Different Electrical Machines .Latvian Journal of Physics and Technical Sciences, vol. 55, no. 4, pp. 13–23, Aug. 2018.

[4] A. N'Diaye, Y. Ait-Amirat, A. Djerdir, R. Pusca, R. Romary. Fault detection through magnetic field measurement of permanent magnet machines with reversed structure. 2017 IEEE Vehicle Power and Propulsion Conference (VPPC), IEEE (2017), pp. 1-6.

[5] M. Galea, L. Papini, H. Zhang, C. Gerada, T. Hamiti. Demagnetization analysis for Halbach array configurations in electrical machines. IEEE Trans Magn, 51 (9) (2015), pp. 1-9.

[6] Sjökvist and S. Eriksson. Experimental Verification of a Simulation Model for Partial Demagnetization Permanent Magnets. IEEE Transactions on Magnetics, April 2014.

[7] S. Zheng, X. Zhu, Z. Xiang, L. Xu, L. Zhang, C.H.T. Lee. Technology trends, challenges, and opportunities of reduced-rare-earth PM motor for modern electric vehicles. Green Energy and Intelligent Transportation 1 (2022).

[8] T. V. Jayaraman. Magnet selection for permanent magnet synchronous machines by decision science. Results in Materials 20 (2023).

[9] R. Hernandez-Millan, J. R. Pacheco-Pimentel, and J.Salinas. Design principles for recycling induction motors, in IEMDC 2001. IEEE International Electric Machines and Drives Conference (Cat. No.01EX485), Cambridge, MA, USA: IEEE, 2001, pp. 782–788.

[10] J. Ormerod. Permanent magnet markets and applications, in: J. Croat, J. Ormerod (Eds.), Modern Permanent Magnets, Wood head publishing, 2022: pp. 403–434.

[11] J.M.D. Coey.Perspective and propects for Rare Earth Permanent Magnets. Engireering, 6 (2020), pp. 119-131.

[12] Y. Konga, D. Xuc, M. Lind. Efficiency modeling and comparison of surface and interior permanent magnet machines for electric vehicle. Energy Reports 9 (2023) 419–426.

[13] R. Hernández-Millán, J. R. Pacheco-Pimentel. Recycling rotating electrical machines. Rev. Fac. Ing. Univ. Antioquia, no. 83, pp. 56–56, Jun. 2017.

[14] M. A. Sellitto. Reverse logistics activities in three companies of the process industry. J. Clean. Prod., vol. 187, pp. 923–931, Jun. 2018.

[15] Z. Li, A. K. Lebouc, J.-M. Dubus, L. Garbuio, S. Personnez. Reuse and Recycle Strategies of Rare Earth Permanent Magnets for Electrical Machines –an overview study. https://hal.science/hal-02981910.

[16] S. Sahni, A. Boustani, T. Gutowski, and S. Steven Graves. Electric Motor Remanufacturing and Energy Savings. Environmentally Benign Laboratory Laboratory for Manufacturing and Productivity Sloan School of Management, Jan. 28, 2010.

[17] R. Liu, Y. Zhao, X. Yang, and G. Wang. Research on High-efficient Remanufacturing Technologies and Application of Electric Motor. IOP Conf. Ser. Mater. Sci. Eng., vol. 231, p. 012102, Sep. 2017.

[18] https://www.femm.info/wiki/HomePage.

[19] Q. Du. Advances in Studies and Applications of Centroidal Voronoi Tessellations. Numer. Math. Theory Methods Appl., vol. 3, no. 2, pp. 119–142, Jun. 2010.

[20] Z. Ullah, B.A. Lodhi and J. Hur. Detection and Identification of Demagnetization and Bearing Faults in PMSM Using Transfer Learning-Based VGG. Energies 2020, 13(15), 3834.