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Reuse and Recycle Strategies of Rare Earth Permanent Magnets for PM Electrical Machines –an overview study

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Abstract - The global supply of heavy rare earth magnets can become risky with the soaring demand of rare earth permanent magnet (PM) machines. One of the promising solutions is to reuse or recycle permanent magnets from End-of-Life electrical machines. This paper is an overview study of the state-of-the-art permanent magnet reuse and recycling research for electrical machines. Some methodologies for quantifying the recyclability of permanent magnet of electrical machines are also introduced.

Key words—Magnets reuse, recycling, PM electrical machines, electrical vehicles, recyclability index.

1. INTRODUCTION

Rare earth PM AC machines are widely used in industry nowadays. Their high efficiency as well as high energy density brings unparalleled superiority. On the one hand, the renewable energy markets are estimated to gain explosive growth in the next decades, such as Hybrid (H) and pure Electrical Vehicles (EV), E-scooter, wind turbines, electrified marines and aircrafts etc. However, on the other hand, the supplies of rare earth are not stable, due to both their geographic distributions and historical issues – the most distinguished event was 2011 rare earth crisis [1].

Hence, there is a serious concern about rare earth supply-demand balance. In order to relieve this risk, one of the important measurements is to recycle the rare earth magnets. From [2], the authors have envisaged three routes for magnets recycling - direct-reuse, direct recycling and indirect recycling magnets, as Figure 1 shows.

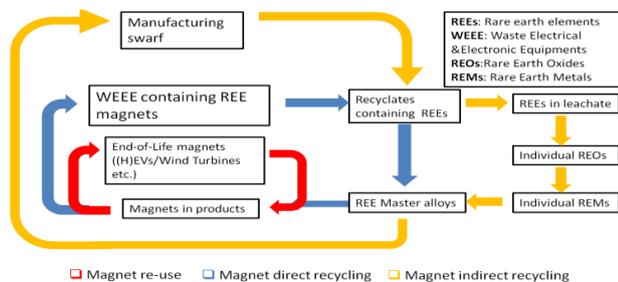


Fig. 1. Three recycling routes for REE permanent magnets from End-of-Life Waste Electrical & Electronic Equipments (WEEEs)

This paper mainly focuses on the route of direct-reuse magnets, sometimes also been called “magnet-to-magnet recycling” [14]. Therefore the magnet reuse and recycle strategies are from the view of machine designs. Unfortunately there were very few articles before summarize these strategies. Although there were projects called MORE [3] which investigated the disassembly of PM electrical machines, their main focus is still on disassembly lines instead of machine design itself. Traditionally, when engineers design electrical machines, they do not consider the recycling stage of the products, such as disassembly problems or materials reuse issues. This paper brings a new dimension into electrical machine design, which considers the aforementioned factors, and mainly focuses on magnets reuse. Besides, after finishing designs with magnets recyclability, for the ease of comparisons between different kinds of electrical machines, it would be better to use special indexes to quantify their recyclability of magnets. Therefore, some novel methodologies which help measuring the recyclability of electrical machines are introduced.

2. DESIGN STRATEGIES FOR PERMANENT MAGNETS REUSE

Here the main design strategies to be implemented for PM reuses have 3 different ways. They are complete magnet reusing, magnet segments reusing which so called “Lego” design and magnet powder reusing respectively.

2.1. Complete magnet reusing

The most straight forward way of reusing permanent magnets is to reuse the whole magnet piece, such as a magnet ring or magnet bulks. For instance, as [4] presented, the rotor is basically a magnet ring made by bonded NdFeB magnets. The magnet ring is magnetized as a continuous Halbach array, which makes the airgap flux sinusoidal concentrated. As for the reason of using bonded magnets instead of sintered magnets, it is mainly due to the high cost and large difficulties of magnetization for sintered magnets. Also unlike sintered magnet, which always need adhesive agent for fixing, bonded magnets do not require it, which results in easy extraction process.

The authors compared the results of the rotors with and without rotor iron back, it is found that due to the shield effect of Halbach array, the iron back has tiny influence on the motor electromagnetic performances, regardless of its

mechanical function. Thus, the rotor can be simply a magnet ring and might be directly reused.

However, the magnet ring designs can only be applied on few scenarios – in order to gain large airgap area and good mechanical strength, normally they are outer rotor design. To sufficiently take the advantages of Halbach array, it always goes to high pole number to obtain high flux concentration on the airgap. In this case, it is better to choose concentrated winding configurations. However, this combination leads to several issues – due to the high pole number, the top speed is limited to relatively low range. There is a high chance to induce large eddy current in the magnet ring due to high sub-harmonics [19]. Only if the resistivity of magnet is high, such as bonded magnet, or segmented magnets, the eddy current can be acceptable. Last but not the least, to reuse the ring for the next new motor design, it has no choice but to keep the rotor shape all the same. However, this is not always feasible in reality. So at the end, the magnet ring is always smashed for producing new magnet again. Thus, there are huge limitations of applying magnet ring in electrical machines.

2.2. “Lego” design

The second way is magnet segments reusing, which is so called “Lego” design. It has more versatility comparing to the first method. As mentioned before, the common problem for magnet reuse is the different magnet shape with the iteration of machine generations. While with “Lego” design, this problem can be reasonably solved. As Figure 2 shown, from (a) to (d), a solid shaped magnet pole can be continuously divided into small and standardized segments. Thus, the small magnet segments can be reused for future generations, no matter what magnets shape they will be.

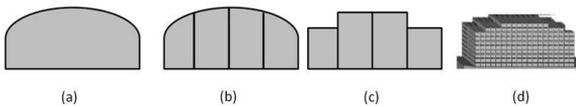


Fig. 2. (a) A solid piece of bread loaf magnet. (b) Segmented bread loaf magnet. (c) Combined rectangular shape magnet. (d) Magnet pole with standard segments for reusing

[5] exactly applied this idea on a Surface mounted Permanent Magnet (SPM) machine with NdFeB magnets for offshore wind turbine application. The magnet poles were not only segmented, but also be enclosed by a stainless steel container in order to prevent corrosion caused by the harsh environment of the ocean. The main purpose of the paper was to investigate if the magnet reuse concept can change the electromagnetic performances of the wind turbine.

The magnet pole was assembled by standard magnet segments with adhesive agent. Although the active magnet space reduced due to the additional glue space, there is only a small reduction of torque and flux linkage. Therefore, the performances of wind turbine have almost no influence by the assembly method. In the paper, only around 5% axial length of the wind turbine was increased for the torque compensation. Besides, now as the shape of the magnet pole can be easily changed, the increased torque ripple and cogging torque which produced by the non-smooth surface of the magnet pole, can be easily cancelled by an appropriate pole shaping. Meanwhile magnet eddy current can be eliminated thanks to segmented magnets.

However, a huge limitation of this method is their costly assembly - massive adhesive agent need to be used, not to mention the strong repulsion forces between each segment

when it is magnetized. Besides, as thermal treatments need to be used for disassembly, the magnet quality may be degraded. In this case, magnet coating is a vital consideration. [6] investigated this problem and found that not all magnet coatings of NdFeB magnets could sustain repeated thermal treatments. The authors compared 4 common coatings respectively: Zn, Epoxy, Ni-Cu-Ni and Ni-Cu+Epoxy. There were also 4 tests for each coating to go through: J-H curves measurements, pull-off test, corrosion test and microscopy check, after 1 and 5 heat cycles respectively. The results showed that no matter what coatings are, the J-H curves always kept the same after both 1 and 5 heating cycles, which means the remanence flux density **Br** and Coercivity **Hc** kept constant after heating. However, for pull-off test and corrosion test, Ni-Cu+Epoxy and Ni-Cu-Ni coatings had much better results than Zn and Epoxy coatings. Finally the authors concluded that Ni-Cu+Epoxy coating is the best choice to protect NdFeB magnets from thermal treatment, while Epoxy coating got the worst performance.

Normally “Lego” design is suit for SPM machine, either radial flux or axial flux. However, for electrical vehicle application, due to the requirements of high speed rotation, SPM machines are not always good candidates. Because SPM machine has some inherent disadvantages of low constant power speed range (CPSR) due to low saliency and high normalized magnet flux linkage. These characteristics also contribute to large short circuit current, which leads to serious thermal issue. Besides, for radial flux inner rotor SPM, the magnets always need to be fixed by a sleeve made of titanium or carbon fiber, which is costly and performances may be degraded [18].

In summary, “Lego” design has many difficulties to be mass produced, and may only suitable for large PM electrical machines, such as wind turbine applications.

2.3. Magnet powder reusing

Following the “Lego” concept, the magnet segment can be eventually divided into magnet powder. Thus, this is called magnet powder reusing. In fact, magnet powder materials are not rare at all - Before magnets sintered or bonded, their states are just powder. Therefore, it is possible to directly form the magnet inside the rotor by special treatments. [7] developed a novel manufacturing method called IP¹ magnet which pressing and sealing NdFeB magnet powder directly into a stainless steel container prior to magnetization, without any bind agent or coating. The advantages are obvious considering the random shape it is able to form, and glue-free production for easy extraction. While no matter how simply it looks to extract magnets, demagnetization is always the first step. Moreover the demagnetized chunks which taken out from the rotor still need to be mechanically crushed again. Thus, the authors investigated the recycled magnets quality after these thermal and mechanical treatments.

It was found that mechanical crushing always caused 10% particle size of the recycled powder smaller than the original size, which resulted in lower Hc. Temperature of demagnetization also influenced the performance of the recycled magnet powder. The ideal demagnetizing temperature was 350 °C, which BH product after re-magnetizing was higher than the other two demagnetizing temperatures 400 and 650 °C. But still no matter what the demagnetization temperature was, there was always around 10% reduction of Br and 20% reduction of Hc.

Nevertheless, currently the direct magnet powder compression method is only for small motor applications (axial length<5cm, outer diameter<5cm). Demonstrations are needed for more powerful applications in the future, such as traction motors in (H)EVs.

[8] on the other hand, provided another magnet powder technique feasible for EV applications. The authors applied a new anisotropic Dysprosium free NdFeB magnet powder with thermoplastic binder. The mixture was injection or compression molded into a rotor of Interior Permanent Magnet Synchronous Machine (IPMSM) with high temperature ambient. Thermoplastic binder can be repeatedly heated up, thus, it is possible to reuse the mixture. Besides, this new magnet has slightly lower remanence flux than sintered NdFeB magnets (0.7T), which enable the possibility to magnetize them inside the rotor, hence reduces the difficulty of magnet insertion step.

For magnet extraction, the rotor can be heated up to Curie's temperature of the bonded magnets. Hence magnets are melted and demagnetized at the same time, and the magnet can be easily removed from the rotor. Afterwards the reused magnet only need to be mixed with a proper proportion of new magnet powder, and then it will be ready for the next generation of motor product.

In summary, the listed three strategies are only aiming at magnet reuse and recycling. In fact, there are some general methods for easy disassembly, which can naturally improve magnet disassembly rate. These general methods always refer to modular designs, such as [15] [16]. However, a common challenge is the complex mechanical support needed for holding each module, no matter it is a joint or a bracket. Nevertheless, [20] had thoroughly reviewed the techniques of modular designs, so there is no need for repeated narrative.

Also apart from physical measurement to extract magnets, there are some novel ways by using chemical treatment. For instance, Hydrogen Decrepitation (HD) is a promising solution for extracting magnet. As [17] demonstrated on hard disk drives, it is also possible to realize it on motor. Although it is called direct magnet recycling, due to additional process steps to recover magnets, it can be used on normal motors without special design for magnets disassembly. Thus, it becomes a very competitive method against motors with concept of magnet-to-magnet recycling.

3. METHODOLOGIES OF RECYCLABILITY INDEXES

It is not enough to only think over new design methods for disassembly. It is also important to evaluate the recyclability between different machines.

The magnet recyclability can be mainly measured by two indexes –One index evaluates the recyclability from the views of assembly and disassembly of motors, considering their standardization and cost. The second index evaluates the impact of motor performances when applying recycled or reused magnets, considering energy consumptions over their usage life cycle. These two indexes together can be called Weighted Index of machines Recycling and Energy consumption (WIRE).

3.1. Weighted Index of Recycling and Disassembly

The first index is introduced in [9]. The methodology is similar to Failure Mode and Effect Analysis (FMEA) process

[10] – the results are obtained by the discussion of a group of experts and scored by their mutual agreement. Therefore, the index can be adjusted and even customized, depending on practical manufacturing conditions and experiences. However, the index is also well defined and goes into fine details level, such as components, materials and each process step. Therefore, the index can be seen as comprehensive and objective. A part of the scoring table is shown in Figure 3. In this table, there are two general columns – Standard and cost. Standard means how common it is for a specific material or process. The more standardized, the higher the score, as it can simplify the recycling process. The meaning of cost is quite straightforward. It can be either a material cost or a process cost. However, bear in mind that the cost here is a relative concept. It does not indicate any real and absolute cost for a certain thing. For instance, a magnet cost in real life can be 50€/kg, an iron cost in real life can be 5€/kg. While in the table sheet, people always give 5 points to the magnet, while 1 point to the iron. Therefore, the scores are only meaningful when people compare different motors with the same assumptions and under the same scenarios.

Then, under the two general columns, there are always two categories that denote “S” and “T”. “S” stands for “Score”, which simply depends on the scale of the respective section. “T” stands for “Importance”, which decide the criticality of the item in terms of recyclability of the materials or the process for recycling. Finally, the product of “S” and “T” outputs the final point of the item. For instance, in the cost part, magnet material can be very expensive, so “S” is 5 points. While the weight of magnets is very small compare to other materials usage, so “T” is given to 1 point. Eventually, magnet section gains “5 points”. In the opposite, for iron material it might be cheap, so “S” is 1 point, while the weight of iron is very high and occupies the biggest portion of the machine weight, thus “T” gets 5 points. At the end iron also gains the same “5 points” as magnet. Apparently, these scorings need to base on real prices and weights data of machines, rather than simply guess or estimate.

Scoring pattern: 0-5
 5 = Highest score
 1 = Lowest score
 3 = Neutral score

Assumption: The motor developed is new and for the first time and manual disassembly with high volumes i.e. 50,000 per annum

MOTOR ID		Halbach motor									
Component/Parts	Remarks	Standard			Cost			Recyclability SCORE			
		S	I	SxI	S	I	SxI	Remarks			
Materials											
- Stator											
Lamination S	segmented stator	5	5	25	good for recycle not reuse	1	5	5		30	
Copper	AWG 24	5	5	25		2	2	4		29	
- Rotor											
Steel R	MS steel	5	5	25	good for recycle not reuse	1	3	3		28	
Magnets	NdFeB-halbach	3	2	6	Halbach cylinder	4	2	8	bonded magnet	14	
- Shaft											
Shaft	Steel	4	5	20	standard shaft	1	2	2	same for all motors	22	
- Endshields											
Drive Side	aluminium die cast	2	5	10	prepare new die	1	2	2	same for all motors	12	
Non-Drive side	aluminium die cast	2	5	10	prepare new die	1	2	2	same for all motors	12	
				32	121			18	26	147	
	Weighted score			75.51%				28.95%			
Component/Parts		Standard			Cost			Recyclability SCORE			

Fig. 3 Evaluation table sheet of materials section for standardization and cost scoring

In the paper, once defining all the assumptions of each material, component and process step, the authors used the index to compare four different motors for DEMETER project. These four motors have implemented strategies of complete magnet ring reusing, modular design, magnet bulks reusing and magnet powder reusing respectively, as figure 4 shows.

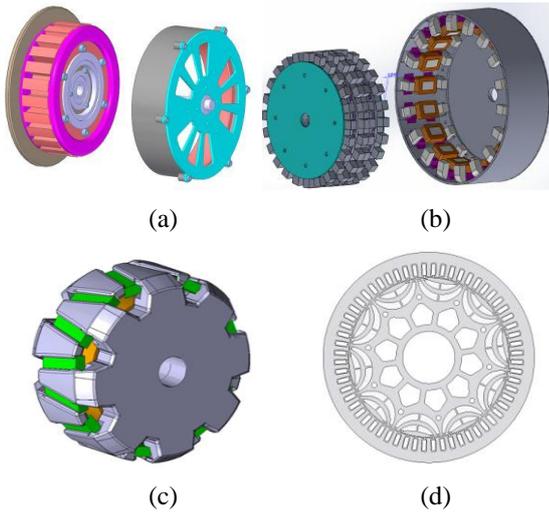


Fig. 4 (a) Outer rotor SPM motor with Halbach Ring, magnet is highlighted in orange color (b) 3D flux hybrid motor with modular stator, magnets are placed in rotor between gear-shape iron plates (c) magnet assisted claw pole motor (rotor), magnets are highlighted in green color (d) IPMSM with direct magnet injection molding, magnets are "boomerang" shape.

Table 1. Summary of magnet reusing strategies from [9]

Reuse strategy	Application scope	Advantages	Disadvantages
Complete magnet reuse(a)(c)	Small	Easy to extract magnet.	- Magnet shape is unchangeable. - Complex magnetization.
Magnet powder reusing(d)	Medium	Can form to any shape for different applications.	Need special tools for assembly and disassembly
Modular design(b)	High	Modular design can apply to most of the machine types.	- Using special materials. - Complex mechanical structure. - Degraded machine performances.

After scoring, it was found that (a) (c) gained higher scores than (b) and (d). The main reason is due to more standard materials and processes used for (a) and (c), while less standard for (b) and (d). Therefore, it indicates from the other side that the methodology has its inherent limitation of innovation exclusion. Because high novel machine designs always need to use unusually materials and assembly process, which make the cost and manufacture difficulties higher. Finally, the advantages and disadvantages of different strategies are summarized in Table 1. The application scope means how widely the design strategy can be used in general motor designs.

3.2. Weighted Index of Energy

The second index is mentioned in [11] [12] respectively. This index reflects the relationship between saved cost from recycled magnets and increased cost from efficiency degradation. First of all, [11] validated the efficiency map between simulation and experiment. The validated motor

was a hub motor normally used for the traction of scooters or mini urban cars, as Figure 5 shows. The experiment test bench is shown in Figure 6.



Fig. 5 (a) Outer rotor and magnets of the hub motor; (b) Inner stator of the hub motor.



Fig.6 Efficiency test bench with Back-to-Back configuration

After considering copper losses, core losses and mechanical losses, the total efficiency of the motor can be obtained. The authors concluded that the simulation results were well coincide with experiment results. Hence following the same simulation principles, [12] calculated the totally energy consumptions of the machines with virgin magnets and with recycled magnets respectively. To do the calculation, several presumptions need to be defined:

1. What are the physical parameters of the car for the motors traction, and how many motors in one car?
2. What drive cycle need to be used, for instance, NEDC or WLTP? How many utilization hours in its life time?
3. Within a drive cycle, are the braking periods, which equivalent to regenerative braking for EVs, considered?
4. What is the performance of the recycled magnet?
5. What are the prices of virgin and recycled magnets respectively, as well as electricity price?

In the paper, the motor was used for an urban pure electric vehicle with light weight and 50km/h maximum speed. There were four identical motors together drive the car. The urban part of NEDC drive cycle, which called ECE-15 drive cycle was applied, as the main project target was for European market. Also the torque and speed requirements of ECE-15 were well align with the performances of the motor. The total usage hours were assumed as 7300h. Regenerative braking periods were not considered in the calculation and directly assumed as zero torque. The performances of recycled magnet were taken from [13], where Br of recycled sintered NdFeB magnets were 20% reduced comparing to the virgin magnets. Finally, the authors assumed a magnet prices matrix to cover a large scope of economic scenarios. The electricity price is taken as the average price of European countries electricity.

Moreover, in order to have a fair comparison, the envelopes of torque speed curve should be basically kept the same between machines with virgin magnets and machines with recycled magnets. To achieve this, the authors simply

increased the axial length of the machine by 15%, as this is a practical way for normal radial flux SPM machines.

With the assumptions above, the calculations for efficiency maps of both machines, as well as final energy consumptions were done. With the energy consumptions of virgin and recycled machines, and with the prices of both magnets, the energy index can be created, as equation (1) shows

$$EC_i = \frac{E_c(j) \text{ Mag}_c(j)}{E_c(b) \text{ Mag}_c(b)} \quad (1)$$

Where EC_i is the energy cost index. $E_c(j)$ is the energy cost of scenario j . $\text{Mag}_c(j)$ is the magnet cost of scenario j . $E_c(b)$ and $\text{Mag}_c(b)$ are the indexes of a base scenario which calculated with virgin magnets usage.

It was found that by applying recycled magnets, the motor even consumed a bit less energy during the whole usage life cycle. This may sound unreasonable. However, as the chosen motor is not dedicated to this drive cycle, and the authors have ignored the regenerative braking period, this result may happen. This from the other point of view proves how important it is to choose proper motor for different applications, instead of a common solution. For the energy index calculation, as currently the cost for recycled magnet is still an ongoing estimation, only assumptions for several scenarios can be made. For instance, an energy cost index matrix is shown in Figure 7.

		VIRGIN MAGNETS						
		PM. mat. price(€/kg)	20	35	50	65	80	95
		PM. cost (€)	14.0	24.5	35.0	45.5	56.0	66.5
RECYCLED MAGNETS	5	4.05	0.282	0.161	0.113	0.087	0.071	0.059
	20	16.20	1.128	0.645	0.451	0.347	0.282	0.237
	35	28.35	1.974	1.128	0.790	0.607	0.494	0.416
	50	40.50	2.820	1.611	1.128	0.868	0.705	0.594
	65	52.65	3.666	2.095	1.466	1.128	0.917	0.772
	80	64.80	4.512	2.578	1.805	1.388	1.128	0.950
	95	76.95	5.358	3.062	2.143	1.649	1.340	1.128

Fig.7 Table sheet of Energy Cost index with assumed virgin magnets and recycled magnets costs

When index equals to 1, it means the saved cost from magnets and extra cost from energy consumption can be balanced. So the smaller index is, the better the motor is for recycling. In Figure 7, the green region indicates positive economic effect for recycling. Conversely, the red region indicates negative economic effect.

Nevertheless, focusing on the urban car application, the authors claimed that it is totally possible to realize the recycled magnets applications commercially. More importantly, this paper demonstrated a methodology for evaluating strategy of using recycled magnets in motors. Thus, depends on the aforementioned 5 assumptions, different applications may lead to different conclusions of the economic effect. Therefore, the index is prone to be a tool for helping people customizes their own solution, instead of giving a certain conclusion. However, it has to be recognized that the degradation of coercivity in recycled magnets cannot be included in this index. This effect is hard to measure as it involves thermal issues. Thus, without fully redesign of the motor, coercivity degradation cannot be overcome.

[21] also discussed the possibility of commercialization for recycled NdFeB magnet used for electrical machines. The authors had similar opinions towards recycled magnets application with [12]. Besides, they found the superiorities of recycled NdFeB magnets over ferrite magnets used for the same motor. These superiorities included higher torque and higher efficiency, within similar demagnetization resistance.

Apart from simply using cost to measure the benefit of recycled magnets, there are other standard from professional Life Cycle Assessment (LCA) point of view, such as CO₂ or pollutions reduction. For instance, [14] compared the global warming potential through life cycle assessment of NdFeB magnets. It is found that by doing magnet-to-magnet recycling, the total environment footprint can be significantly lower than using virgin magnets.

4. CONCLUSIONS

The study has summarized the recent literatures of magnet reuse and recycling strategies for electrical machines, as well as indexes for recyclability measurements and comparisons. It is found that different magnet reusing strategies need to be applied depend on different applications. Besides, theoretically it proves that, if magnets reusing can be considered in machine design phase, it can bring profit from the view of cost and energy saving. In the future, the collection and labor cost for end-of-life motors will be the other vital issues for the commercialization of magnet recycling applications. In fact, the study only introduces a small area of recycling strategies. From other prospects, like modular designs, or chemical treatments (i.e. Hydrogen Decrepiation process for NdFeB magnets), it can have a huge potential to enable easy and cheap routes of recycling rare earth permanent magnets from electrical machines.

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6. REFERENCES

- [1] K. Bourzac, "The rare-earth crisis. MIT Technology Review. <http://www.technologyreview.com/featuredstory/423730/the-rare-earth-crisis/> " 2011.
- [2] K. Binnemans, P. T. Jones, T. Müller, L. Yurramendi, "Rare Earths and the Balance Problem: How to Deal with Changing Markets," *Journal of Sustainable Metallurgy*, 2018.
- [3] U. Bast, F. Treffer, C. Thürigen, T. Elwert, F. Marscheider-Weidemann, "Recycling von Komponenten und strategischen Metallen aus elektrischen Fahrerantrieben," *Recycling und Rohstoffe, Bd, vol 5, 2014*.
- [4] A. K. Jha, L. Garbuio, A. Kedous-Lebouc, J. P. Yonnet, J. M. Dubus, "Design and comparison of outer rotor bonded magnets Halbach motor with different topologies. In *Electrical Machines, Drives and Power Systems*" ELMA, 15th International Conference on (pp. 6-10). IEEE. June, 2017.
- [5] S. Hogberg, T. S. Pedersen, B. B. Jensen, N. Mijatovic, J. Holboll, "Direct Reuse of Rare Earth Permanent Magnets -Wind Turbine Generator Case Study," *ICEM*, 2016.
- [6] S. Hogberg, J. Holboll, N. Mijatovic, B. B. Jensen, F. B. Bendixen, "Direct Reuse of Rare Earth Permanent Magnets-Coating Integrity," vol. 53, no. 4, p. 1-9, *IEEE Transactions on Magnetics, IEEE*, 2016.
- [7] S. Högberg, F. B. Bendixen, N. Mijatovic, B. B. Jensen, J. Holb, "Influence of demagnetization-temperature on magnetic performance of recycled Nd-Fe-B magnets," *In Electric Machines & Drives Conference (IEMDC) on (pp. 1242-1246), IEEE International, May 2015*.

- [8] Z. Li, A. Kedous-Lebouc, J. M. Dubus, R. Fratila, J. Legranger, "Investigation on IPMSM Machines with Dy-free Magnets and Magnets recycling Concept for Hybrid Electrical Vehicle Applications," ECCE 2018, under review, accepted.
- [9] A. K. Jha, Z. Li, A. G. Gonzalez, P. Upadhayay, P. O. Rasmussen, A. Kedous-Lebouc, L. Garbuio, "Weighted Index of Recycling and Energy Cost for motors in Electric Vehicles," Speedam, 2018, submitted.
- [10] S. H. Teng, S. Y. Ho, "Failure mode and effects analysis: an integrated approach for product design and process control", *International journal of quality & reliability management*, vol. 13(5), pp. 8-26, 1996.
- [11] A. G. Gonzalez, A. K. Jha, Z. Li, P. Upadhayay, P. O. Rasmussen "Validation of Efficiency Maps of an Outer Rotor Surface Mounted Permanent Magnet Machine for Evaluation of Recyclability of Magnets", *Intermag* 2018.
- [12] P. Upadhayay, A. G. Gonzalez, Z. Li, A. K. Jha, P. O. Rasmussen, A. Kedous-Lebouc, J. C. Mipo, "Evaluation of Energy Cost Index for an Electric Vehicle Motor over a particular Drive Cycle with Recycled Magnet Concept", *ICEM* 2018, under review, submitted.
- [13] R. S. Sheridan, A. J. Williams, I. R. Harris, A. Walton, "Improved HDDR processing route for production of anisotropic powder from sintered NdFeB type magnets", *Journal of Magnetism and Magnetic Materials*, vol. 350, pp. 114-118, 2014.
- [14] H. Jin, P. Afiuny, S. Dove, G. Furlan, M. Zakotnik, Y. Yih, J. W. Sutherland, "Life Cycle Assessment of Neodymium-Iron-Boron Magnet-to-Magnet Recycling for Electric Vehicle Motors", *Environmental science & technology*, 2018.
- [15] C. Henaux, B. Nogarede, D. Harribey, "A new concept of modular permanent magnet and soft magnetic compound motor dedicated to widespread application", *Magnetics, IEEE Transactions*, vol. 48, p. 2035-2043, 2012
- [16] T. J. Woolmer, M. D. McCulloch, "Analysis of the yokeless and segmented armature machine. In *Electric Machines & Drives Conference*", *IEMDC'07, IEEE International*, vol. 1, pp. 704-708, 2007.
- [17] A. Walton, H. Yi, N. Rowson, J. Speight, V. Mann, R. Sheridan, A. Bradshaw, I. Harris, A. Williams, "The use of hydrogen to separate and recycle neodymium--iron--boron-type magnets from electronic waste", *Journal of Cleaner Production, Elsevier*, vol. 104, pp. 236-241, 2015
- [18] Z. Li, A. Kedous-Lebouc, R. Fratila, J. Legranger, J. M. Dubus, A. Ikram, "Investigation on surface mounted PM machines with magnet recycling concept for hybrid electrical vehicle applications. In *Electrical Machines and Systems*", 20th ICEMS, IEEE, pp. 1-6, 2017.
- [19] A. K. Jha, A. Kedous-Lebouc, L. Garbuio, J. P. Yonnet, J. M. Dubus, "FEA based analysis on effect of slot pole combination on motor torque and magnet eddy current loss with bonded NdFeB Halbach rotor", In *Electrical Machines and Systems (ICEMS), 2017 20th International Conference on* (pp. 1-5). IEEE.
- [20] Z. Q. Zhu, Y. X. Li, "Modularity techniques in high performance permanent magnet machines and applications," *CES Transactions on Electrical Machines and Systems*, vol. 2, no 1, p. 93-103, 2018.
- [21] M. Kimiabeigi, R. S. Sheridan, J. D. Widmer, A. Walton, M. Farr, B. Scholes, I. R. Harris, "Production and Application of HPMS Recycled Bonded Permanent Magnets for a Traction Motor Application", *IEEE Transactions on Industrial Electronics*, vol. 65, no.5, p. 3795-3804, 2018