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Recycling rotating electrical machines

Reciclaje de máquinas eléctricas rotativas

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ABSTRACT: This paper establishes design principles for rotating recyclable electrical machines (synchronous and induction), in other words electrical machines and machine components may be reused. Also, technological issues arising from following machine components are covered: stator core, rotor core, stator windings, rotor windings, bearings, shafts, and frames. Design principles discussed may be extended to transformers. Insulation materials in high voltage windings are not considered. This paper did not consider economic advantages of the processes, neither environmental consequences. Rotating machines considered in the present study are of a power range within 0.1 kW to 400 kW, frequencies 50 hertz and 60 hertz and poles 2, 4 and 6 although the general concepts could be applied to other machines. Required machine standards to achieve these goals are discussed, covering: speed, nominal voltage, capacities, shapes, dimensions, insulation, cores, windings, bearings, shafts and frames.

RESUMEN: Este trabajo establece los principios de diseño para el reciclaje de máquinas eléctricas rotativas (sincrónicas y de inducción), en otras palabras, las máquinas eléctricas y sus componentes pueden ser reutilizados. Además, se cubren temas tecnológicos surgidos de las siguientes componentes de la máquina: núcleo del estator y rotor, devanados del estator y rotor, cojinetes, ejes, y carcasas. Los principios de diseño discutidos pueden extenderse a los transformadores. Este trabajo no consideró materiales de aislamiento en devanados de alta tensión. La economía de reciclaje no se discute ni consecuencias ambientales. Las máquinas rotativas consideradas en el presente estudio son de un rango de potencia entre 0,1 kW a 400 kW, frecuencias de 50 hertz y 60 hertz y polos 2, 4 y 6, aunque los conceptos generales podrían aplicarse a otras máquinas. Se discuten las normas de máquina necesarios para lograr estos objetivos, que abarca: velocidad, tensión nominal, capacidades, formas, dimensiones, de aislamiento, de los devanados, cojinetes, ejes y carcasas.

1. Introduction

The first paper on recycling electrical machines was published by us in 2000 and presented early ideas on this subject [1]. Likewise, The Directive of the European Parliament in 2002 on waste electrical and electronic equipment (WEEE) introduced new regulations. "The purpose of this Directive is to contribute to sustainable production and consumption by as priority, the prevention of WEEE and in addition, by the reuse, recycling and other forms of recovery of such wastes so as to reduce the disposal of waste and to contribute to the efficient use of resources and the retrieval of valuable secondary raw materials" [2]. These legislative efforts have begun to mandate recycling and manufacturer "take back". European regulations ask, "electrical motors manufacturers to provide relevant information on disassembly, recycling or disposal at end-of-life" of an electrical motor. This regulation is a call to manage the life-cycle of an electrical machine [2, 3].

The Space Shuttle Solid Rocket Booster (SRB) has the largest motor ever designed to be reused. The spent SRBs were recovered from the ocean, remanufactured, reloaded with propellant, and reused for a new mission. Over 5,000 components from the SRBs are remanufactured after each flight and reused. SRBs were remanufactured for economic reasons [4]. The new Falcon rocket is designed to be recovered, remanufactured and reused too.

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The rewinding and other repair processes of induction motors are considered as recycling and are covered by standards [5]. There are several standards for maintaining, repairing and testing insulation in rotating electrical machines and coils. These standards may be the foundations for remanufacturing standards for rotating electrical machines. Electrical machines manufacturers are developing new recycling practices too.

This paper presents a set of definitions and a group of cases researched by us to recycle electrical machines. We do not suggest storing old, questionable components until they are needed. We propose distributed manufacturing and distributed recycling of electrical machines. In traditional electrical machines manufacturing, raw materials are brought together, assembled and fabricated in factories into finished products. In distributed manufacturing and distributed recycling, the raw materials, components manufacturing and methods of fabrication are decentralized, and the final product is manufactured close to the final customer.

2. Definitions (6, 7)

2.1. Raw materials

A raw material is the basic material from which a product is manufactured or made.

2.2. Products

Product is a "thing produced by labor or effort" or the "result of an act or a process" [6]. A product is made of components and complies with a set of specifications.

2.3. Components

Components are parts of a product that comply with a set of specifications. A component is a product too.

2.4. Manufacturing

"Manufacturing is the process of converting raw materials, processed materials and components into products" [6].

2.5. Processed materials

Processed materials are materials that have been refined or built by humans from raw materials. Examples: paper, steel, or glass.

2.6. A rebuilt product

A rebuilt product is a new product created using discarded products, raw materials, processed materials and components. Rebuilding recovers the residual value added to a product at the end of its life.

2.7. Recycling

"Recycling means reusing a material or a component or a product not necessarily in its original form" [7]. The adoption of recycling techniques allied with good design practice can do much to conserve raw materials and energy if we allow for materials and components to be reclaimed from products after their useful life is over, we minimize waste and we save money. Waste minimization followed by recycling does offer the potential for considerable savings without major sacrifices on the part of the consumer. Figures 1 and 2 depict the life process of a product and an electrical machine respectively [8]. Recycling may take place at the end-of-life of an electrical machine or at any stage of the life process of an electrical machine [9].

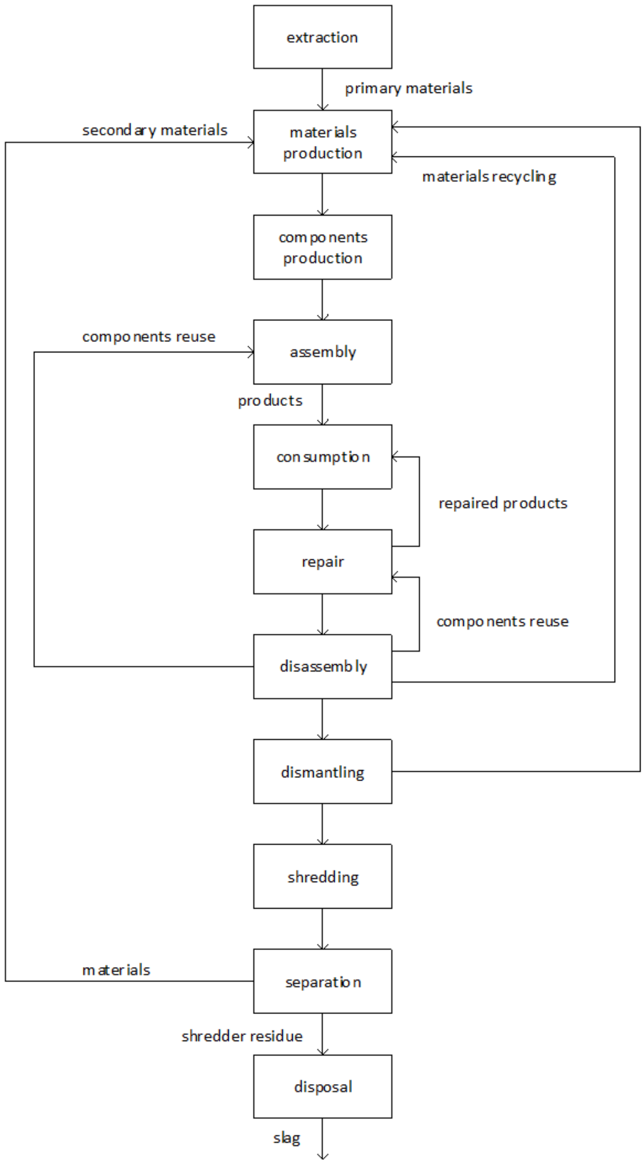

Figure 1 Disaggregated product-process chain of a product life [4]

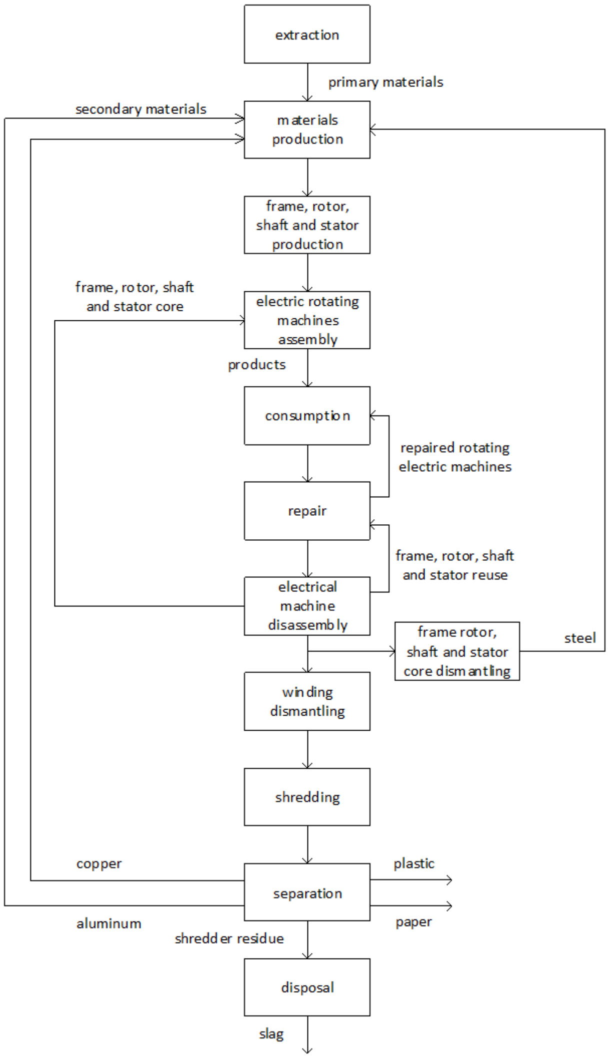

Figure 2 Disaggregated product-process chain of a rotating electrical machine life

2.8. Recycling classes (7)

The first class is the reuse of materials or components. "An example of the first class is typified by the returnable bottle, which makes several trips from bottler to consumer and back again where it is cleaned and refilled" [7]. Reuse may be allocated the highest value in the recycling classes in that least energy and process complexity is normally expended in getting the material or article back into use. Typical reused items are compressed gas cylinders, the 200-litre drum (a worldwide standard) and the intermodal container (also a worldwide standard). The frame of a rotating electrical machine or the tank of a transformer could be another example. A special case of the first class of recycling is remanufacturing. In this paper remanufacturing is "the process of returning a used product to original-equipment-manufacturer performance specification and giving the resultant product a warranty equal to that of a newly manufactured equivalent" [10]. Repair is in this paper: "the correction of specified faults in a product".

The second class is direct recycling. "An example of the second class is the returnable bottle as our first example; once the bottle is unfit for reuse and the bottle is cleaned and broken down to cullet at the glass-works and used to make more bottles. The most direct recycling occurs at the factory where the product is made, e.g. broken bottles fed back to the melting chamber" [7]. All conductor material in windings at end-of-life of an electrical machine may be recycled directly. Also, frame materials, shaft materials, transformer oil, conductors in windings and metals in magnetic cores may be recycled directly. Direct recycling has an intermediate availability in that both energy expenditure and process complexity may be required in getting the material back into use.

"The third class is indirect recycling. Continuing with our glass bottle, it is probable that it will end up in domestic refuse where it can be extracted by screening and separation. These bottles will be of different colors and varying degrees of cleanliness and are unsuitable for cullet use unless costly optical sorting is used" [7]. The bottles may be ground up and used for a skid-resistant road-surfacing material. Similarly, electrical insulation solids may end up as road-surfacing materials too. Indirect recycling is the lowest form of recycling. Normally, once processed in this phase, the material is no longer available for use except for landfill or incineration.

2.9. Electrical machine

An electrical machine is the generic name for a product that converts mechanical energy to electrical energy, converts electrical energy to mechanical energy, or a product, the transformer, that transfers electrical energy from one circuit to another through inductively coupled conductors. Electrical machines are divided into three main categories based on how it converts energy. Generators convert mechanical energy to electrical energy. Motors convert electrical energy to mechanical energy. Transformers transfer electrical energy between coupled conductors.

2.10. A rotating electrical machine

A rotating electrical machine is the generic name for a rotating product that converts mechanical energy to electrical energy or converts electrical energy to mechanical energy.

2.11. An electrical machine designed for recycling purposes

"An electrical machine designed for recycling purposes is a machine easy to assemble and easy to disassemble. A component of an electrical machine designed for recycling purposes is a component easy to assemble and easy to disassemble too" [1, 11]. Such electrical machine uses materials that do not age significantly on operation, or it uses materials that can be restored economically to un-aged specifications or it uses materials whose electrical, magnetic and mechanical characteristics qualify as non-aged or improve with aging; such electrical machine components may be used economically on another machine. Electrical machines designed to be recycled have high reliability and availability, low initial and operating costs and low losses.

Industry tendencies on rotating electrical machines manufacturing will see more original-equipment-manufacturers outsourcing development of rotating machines components. We anticipate a world of cooperation where [11]:

- Component developers as insulation and ferromagnetic sheet producers, coil and core manufacturers, shaft and frame builders will form partnerships or will establish strategic alliances to share designs and information for machine developments.
- Original-equipment-manufacturers will assume more the role of integrators.
- There will be competition based upon specialized knowledge and scale production (trade based upon specialization using comparative advantages).
- Low cost component developers will expand their operations to capture and internalize technology.

3. Study cases

3.1. Ferromagnetic cores (12)

Ferromagnetic cores are generally the largest and heaviest components of an electrical machine. Soft magnetic cores for electrical machines require magnetic materials known as silicon-steel. But, few instances of recycling applications have been identified for silicon-steel besides direct recycling as steel. Steel is the most recycled metal, but when silicon-steel is recycled directly ferromagnetic properties are not recovered. Silicon acts as contaminant and only small amounts of silicon-steel can be added in each melting batch. Additional processing is needed to achieve magnetic properties.

Recycling options of ferromagnetic cores must be assessed evaluating aging mechanisms (aging coefficient). Silicon-steel ferromagnetic properties change little with use. This aging is associated with increases in core loss and magnetizing current. A positive value of the aging coefficient indicates an increase in losses or a decrease in permeability. However, insulating coating between sheets can age.

With proper processes and techniques, silicon-steel ferromagnetic cores from large transformers after end-of-life can be reused in new cores of, if these new cores comply with specifications. Also, if these new cores have same guarantees as they were manufactured with virgin silicon-steel, the new owner of the electrical machine will have all its needs satisfied. We do not suggest manufacturing ferromagnetic cores with old, lower quality silicon steel.

Since the introduction of amorphous core transformers for electric power distribution in 1991, these devices are now coming due for disposal. In response, the industry recycles the amorphous cores of the transformers into ferro-boron, and has been operating this process since 2009. The possibility of recycling the ferro-boron directly as amorphous alloy could make a sustainable closed loop, the production, operation, and disposal phases of distribution transformers cores [13].

A compacted powdered iron core utilizes iron powder, which is first coated with a silicate and then over coated with a resin. The treated powder is compressed and then annealed. This results in a core component characterized by overall core losses as low as in conventional laminated cores. At the end life of an electrical machine using powdered iron cores, the iron powder might be recovered and reused as an already processed material [13].

Permanent magnets can be reused too, but these special situations do not represent meaningful quantities, although these applications can have strategic meaning [14].

3.2. Squirrel cage rotors

The squirrel cage rotor is a component of an induction motor where the winding and the core cannot be disassembled easily. Reuse of the assembled squirrel cage rotor is a practical manner to handle recycling for this component.

Ideally, squirrel cage rotors should be exchanged with machines of same capacity and different manufacturers. To achieve this objective, stator and rotor cores must be of standard dimensions, i.e. length of active parts, diameters and air gaps. Dimensions of squirrel cages and the rotor cooling system should comply with standards too.

We present in Table 1, suggested standard air gaps for induction motors as a function of mechanical power output and synchronous speed for medium size, induction motors, totally enclosed construction, class B insulation (design B) and 60 hertz. These air gaps were determined using empirical equations and adjustments from experience [15].

External mounting standard dimensions and preferred output values of medium size induction motors are defined in IEC and NEMA standards to assure interchangeability of machines [16-19]. We propose to add to these standard dimensions, three internal dimensions: the air gap, the rotor diameter and the ferromagnetic stator active length for specified induction motors and preferred output values. The air gap could be measured in millimeter and defined up to one tenth of a millimeter. For example, an air gap of 0.9 mm may be referred as gauge 9 air gap. Also, an air gap of 1.6 mm could be referred as gauge 16 air gap. The rotor diameter could be measured in millimeter too and defined up to one millimeter. For example, a rotor diameter of 254.0 mm will be referred as rotor diameter gauge 254. The ferromagnetic stator active length could be measured in millimeter too and defined up to one millimeter using same gauges. We present in Table 2, suggested standard diameters for squirrel cage rotors and in Table 3, suggested standard rotor ferromagnetic active lengths for same machines as described for Table 1 [15-19].

Table 1 Suggested standard air gaps induction motors (mm) (totally enclosed induction motors)

Power/Hp	Synchronous speed (rpm)			
	3600	1800	1200	900
1	0.4	0.3	0.3	0.3
1.5	0.4	0.3	0.3	0.3
2	0.4	0.3	0.3	0.3
3	0.4	0.3	0.3	0.3
5	0.5	0.4	0.4	0.4
7	0.5	0.4	0.4	0.4
10	0.6	0.4	0.4	0.4
15	0.6	0.4	0.4	0.4
20	0.7	0.5	0.5	0.5
25	0.7	0.5	0.5	0.5
30	0.7	0.5	0.5	0.5
40	0.8	0.6	0.6	0.6
50	0.9	0.6	0.6	0.6
60	0.9	0.6	0.6	0.6
75	1.0	0.7	0.7	0.7
100	1.1	0.7	0.7	0.7
125	1.2	0.8	0.8	0.8
150	1.2	0.8	0.8	0.8

We know, standard sizes (Tables 1, 2 and 3) do not consider voltage, starting torque requirements, special applications, specific KVA/HP or atmospheric requirements, but, we consider electrical machines should be manufactured with standard dimensions to be developed, and cost reductions are achieved.

Table 2 Suggested standard diameters squirrel cage rotors (mm) (totally enclosed induction motors, no cooling channels)

Power/Hp	Synchronous speed (rpm)			
	3600	1800	1200	900
1	50	66	80	90
1.5	54	76	91	104
2	60	83	100	114
3	68	95	115	130
5	81	113	136	155
7	89	131	152	173
10	98	141	186	195
15	110	156	203	225
20	119	169	216	242
25	125	178	223	261
30	131	189	236	277
40	142	203	255	299
50	153	216	270	317
60	162	228	287	337
75	174	245	307	361
100	192	269	321	372
125	202	290	342	398
150	212	293	361	421

Table 3 Suggested effective lengths squirrel cage rotors (mm) (totally enclosed induction motors, no cooling channels)

Power/Hp	Synchronous speed (rpm)			
	3600	1800	1200	900
1	79	65	60	56
1.5	84	74	68	64
2	93	82	75	70
3	106	94	86	81
5	125	111	102	96
7	138	129	114	107
10	152	139	140	121
15	171	154	153	139
20	185	166	162	150
25	195	175	167	162
30	205	186	177	172
40	222	200	192	185
50	238	212	203	197
60	253	225	215	209
75	272	241	231	224
100	299	265	241	230
125	315	285	256	247
150	330	288	271	261

3.3. Claw rotors (6, 20)

Claw rotors are easy to disassemble and these rotors offer more flexibility to recycle than squirrel cage rotors. The rotor can use permanent magnets that can be reused too. The claw rotor could be recycled as a component in the same manner a squirrel cage rotor can be recycled and these electrical machines must use standard dimensions too (air gap, rotor diameter, active rotor length).

3.4. Small motors for home laundry equipment

Small single phase motors illustrate the recycling problem presented by large numbers of electrical machines used by the consumer. The main consideration in this section is for the single-phase motor of fractional horse power capacity found in home laundry equipment like a home washing machine, drier or combination washer-drier [3, 21]. Similar cases are found in small dc motors in cars manufactured today and in the future, the driving motor of an electrical car [14]. As all large scale operations, the financial result of the operation is the first consideration.

Small single phase motors of the kind discussed are found worldwide in about 500 million appliances with more than 50 million appliances at end-of-life yearly. There are also take-back appliances policies, both in the European Union and in China [2, 21]. It is anticipated, soon, appliances will be collected at some locations distributed worldwide. Our consideration is to collect those single-phase motors and to recycle them. Again, motors should be standardized in power ratings, speed and dimension and a large operation for motors automatic disassemble and components reuse could be thought. Motor-frames and squirrel cage rotors could be reused and stator steel and copper could be recycled directly.

3.5. Mid-size induction motors 1 Hp-200 Hp

Our estimation of the mid-size induction motors installed base was about 300 million machines worldwide with about 20 million machines at end-of-life yearly. This group offers a case of a large-scale remanufacturing operation.

The remanufacturing of the squirrel cage rotors has been discussed already. To remanufacture the stator, we may have to consider the stator electromagnetic core and the frame as a single component to avoid disassembling the core.

4. Standards for recycling (1, 11)

To recycle, we need common dimensions for electrical machine components. Standards have been developed mainly for the external relations of an electrical machine with its environment. Few standards are available for electrical machines components. This situation is a consequence of little consideration given to recycling and a standard preparation system dominated by manufacturers, industries, researchers and utilities. The consumer and other parts of society participate less in standard preparations.

Following components need standard dimensions:

a) Transformer cores (Standardizing on core laminations would not hinder creativity, design and create obstacles for technological advancement) and transformer tanks,

b) Stators, rotors, air gaps as a function of electrical machine type, frame, nominal power, poles, etcetera,

c) Squirrel cage rotors and claw rotors, and

d) Ventilation system.

e) Also, standards for remanufacturing electrical machines and electrical machines components are required.

5. Conclusions

A robust set of definitions and a disaggregated product process chain of a rotating electrical machine life have been presented. All recycling electrical machines processes are business processes. Insufficiency of recycling rotating electrical machines knowledge can be considered a major problem. This insufficiency grows when higher value added recycling processes are considered as remanufacturing.

Remanufacturing electrical machines may produce profits because normally the cost of conventional manufacturing exceeds that of remanufacturing electrical machines. Remanufacturers of electrical machines would benefit from contracts between original-equipment-manufacturers and remanufacturers to have access to products and components design information. Cases studied describe two groups of induction machines that might become business proposals: Small motors for home laundry equipment and mid-size induction motors 1 Hp-200 Hp.

Remanufacturing is established mainly when products have a long useful life and stable technologies. Electrical machines efficiency improvements and new speed control systems are technology changes being deployed that has to be accounted for. Another business proposal is to reuse silicon-steel ferromagnetic cores from large transformers after end-of-life in applications to be developed. Recycling amorphous cores in electric power distribution transformers is an established closed loop process.

The research presented in this paper offers a new line of inquiry of how to construct electrical machines that comply with recycling requirements.

6. Future works

Our group will prepare suggestions for standard dimensions (air gap, lengths and internal and external diameters of ferromagnetic cores) as a function of discrete nominal power, voltage and number of poles, frequencies of 50 Hertz and 60 Hertz for different types of induction machines. Our group will present suggestions for remanufacturing electrical machines standards. On the other hand, we will be considering the new trends in the materials to be used. The use of new materials such as rare earths in motor applications used for traction is an example to be developed for recycling rotating electrical machines [22].

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8. References

1. R. Hernández, J. Salinas, and J. R. Pacheco, "Design principles for recycling large electric machinery," in *International Conference on Electrical Machines* (ICEM), Espoo, Finland, 2000, pp. 1679-1682.
2. European Parliament, Council of the European Union, *Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE)*, 2012. [Online]. Available: https://goo.gl/QIBg1c. Accessed on: Apr. 15, 2016.
3. M. O'Connell, C. Fitzpatrick, and S. Hickey, "WEEE Reuse Trials in Ireland," in *IEEE International Symposium on Sustainable Systems and Technology* (ISSST), Chicago, USA, 2011, pp. 1-6.

4. C. Moskowitz, *Florida Spaceport Gets Upgrade for New Rocket [Slide Show]*, 2014. [Online]. Available: https://goo.gl/ATtK7e. Accessed on: Apr. 19, 2016.
5. IEEE, *IEEE Standard for the Repair and Rewinding of AC Electric Motors in the Petroleum, Chemical, and Process Industries*, IEEE Standard 1068, 2009.
6. R. C. Creese, *Introduction to manufacturing processes and materials,* 1st ed. Morgantwon, USA: CRC Press, 1999.
7. A. Porteous, *Dictionary of Environmental Science and Technology*, 4th ed. Chichester, UK: John Wiley & Sons, 2008.
8. A. Lambert and S. M. Gupta, *Disassembly Modeling for Assembly, Maintenance, Reuse and Recycling,* 1st ed. Boca Raton, USA: CRC Press, 2005.
9. British Standards Institution (BSI), *Design for manufacture, assembly, disassembly and end-of-life processing (MADE). The process of remanufacture, Specification*, BSI Standard 8887-220, 2010.
10. W. L. Ijomah, "A model-based definition of the generic remanufacturing business process," Ph.D. dissertation, University of Plymouth, Plymouth, UK, 2002.
11. R. Hernández, J. Salinas, and J. R. Pacheco, "Design principles for recycling induction motors," in *IEEE International Electric Machines and Drives Conference* (IEMDC), Cambridge, USA, 2001, pp. 782-788.
12. Z. Godec, "Aging of grain-oriented electrical steel strips," *IEEE Transactions on Magnetics,* vol. 14, no. 1, pp. 9-13, 1978.
13. K. Baba *et al.*, "Hitachi's Involvement in Material Resource Recycling," *Hitachi Review*, vol. 59, no. 4, pp. 180-187, 2010.
14. S. T. Lundmark and M. Alatalo, "A segmented claw-pole motor for traction applications considering recycling aspects," in *8th International Conference and Exhibition on Ecological Vehicles and Renewable Energies* (EVER), Monte Carlo, Monaco, 2013, pp. 1-6.
15. J. Pyrhonen, T. Jokinen, and V. Hrabovcova, *Design of Rotating Electrical Machines*, 2nd ed. New York, USA: John Wiley & Sons, 2013.
16. International Electrotechnical Commission (IEC), *Dimensions and output series for rotating electrical machines - Part 1: Frame numbers 56 to 400 and flange numbers 55 to 1080*, Standard IEC 60072-1, 1991.
17. International Electrotechnical Commision (IEC), *Dimensions and output series for rotating electrical machines - Part 2: Frame numbers 355 to 1000 and flange numbers 1180 to 2360*, Standard IEC 60072-2, 1990.
18. International Electrotechnical Commision (IEC), *Dimensions and output series for rotating electrical machines - Part 3: Small built-in motors - Flange numbers BF10 to BF50*, Standard IEC 60072-3, 1994.
19. National Electrical Manufacturers Association (NEMA), *Motors and Generators*, Standard NEMA MG-1, 2011.
20. Z. Li, *Why we need a new motor design suited for magnets recycling?*, 2016. [Online]. Available: https://goo.gl/ETJVFz. Accessed on: Mar. 11, 2016.
21. M. Xiangru, Z. Yongjie, and S. Wei, "Network Construction on Reverse Logistics of Discarded and Used Household Appliances," in *International Conference on Environmental Science and Information Application Technology,* Wuhan, China, 2009, pp. 108-111.
22. J. D. Widmer, R. Martin, and M. Kimiabeigi, "Electric vehicle traction motors without rare earth magnets," *Sustainable Materials and Technologies*, vol. 3, pp. 7-13, 2015.