www.ietdl.org

Published in IET Electric Power Applications
Received on 18th October 2011
Revised on 29th February 2012
doi: 10.1049/iet-epa.2011.0320

ISSN 1751-8660

Environmental and life cycle cost analysis of one switched reluctance motor drive and two inverter-fed induction motor drives

P. Andrada B. Blanqué E. Martínez J.I. Perat J.A. Sánchez M. Torrent

Grup d'Accionaments Elèctrics amb Commutació Electrònica (GAECE), EPS d'Enginyeria de Vilanova i la Geltrú,
Departament d'Enginyeria Elèctrica, Universitat Politècnica de Catalunya (UPC), Av. Victor Balaguer1, 08800 Vilanova i la Geltrú, Spain
E-mail: pere.andrada@upc.edu

Abstract: Herein is described an environmental and life cycle cost (LCC) analysis of one switched reluctance motor (SRM) drive and two inverter-fed induction motor (IM) drives. The two types of drives are compared based on critical reasoning, and European Commission (EC) Regulation 640/2009 is considered. Environmental impact and LCC were evaluated according the Methodology for the Ecodesign of Energy-Using Products and accounting different operation conditions. The SRM drive was found to have less environmental impact than were the IM drives.

1 Introduction

In 2008, annual world consumption in primary energy was 12.267 Mtoe. Most (81%) of this energy comes from fossil fuels [1]. Unbridled consumption of coal, oil and natural gas has accelerated the depletion of their deposits, increased atmospheric pollution and significantly contributed to global warming. Thus, to stop fossil fuel waste and consequences, energy conservation initiatives are urgently needed.

A major portion of consumed primary energy is converted to electrical energy. In industrialised countries, nearly two-thirds of electrical energy is used to feed electric motors. In fact, in the European Union (EU) in 2005, energy consumption for electric motors during the use phase was 1067 TWh, corresponding to 427 Mt of CO_2 emissions [2]. According to predictions, unless limitations on energy consumption are enacted, motor energy consumption in the use phase is predicted to increase to 1252 TWh by 2020. Therefore electric motors must be made more efficient, to enable energy savings and a reduction in emissions. Regulations establishing minimum efficiencies for electric motors have been created in the USA, Canada, Australia and, more recently, in the EU. Some associations – among the most important of which is NEMA – have defined a classification scheme for electric motors with higher efficiencies (premium efficiency motors).

Given the European context of the present work, the authors considered that a brief explanation on electric motors efficiency regulation in the EU would be apropos. The current European efficiency levels were adopted in a voluntary agreement supported by the European Committee of Manufacturers of Electrical Machines and Power Electronics (CEMEP) and the European Commission (EC), based on testing methods and limits of acceptance defined under the IEC 60034-2: 1996 [3]. Regulation 640/2009 EC [4], implementing Directive 2005/32/EC, establishes eco-design requirements for electric motors and variable speed drives in terms of energy efficiency levels. New efficiency levels were recently defined in standard IEC 60034-30:2008, based on the test methods and limits of acceptance indicated under IEC 60034-2-1:2007. Ecodesign requirements for electric motors will be applied according to the timetable shown in Table 1, which compares the CEMEP/EU agreement with Regulation 640/2009.

Although Regulation 640/2009 represents some progress in energy conservation, as it establishes ecodesign requirements for the placing on the market and for putting in service of electric motors, it addresses only the use phase (electricity consumption). However, focusing exclusively on consumption is no longer sufficient; energy savings initiatives must now account for all life cycle costs (LCC), including production, use and disposal. A useful tool for evaluating LCC is the Methodology for the Ecodesign of Energy-Using Products (MEEUP), which was developed to determine whether, and to what extent, a product meets the criteria stipulated in the Directive on the Ecodesign of Energy-Using Products (EuP 2005/32/EC).

Electric motors are usually identified with three-phase induction motors and variable speed drives with inverter-fed induction motor (IM) drives. Nevertheless, recently, there have been significant advances in the field of variable speed drives, in which the electric motor involved is not the three-phase induction motor. These motors share one feature, unlike the three-phase induction motor; they can only be operated when they are associated with electronic control

Table 1 Comparison of the CEMEP/EU agreement and regulation 640/2009

	CEMEP/EU agreement	Regulation 640/2009
number of poles	2 or 4	2,4 or 6
voltage	400 V, 50 Hz	$<$1000 V, 50/60 Hz
power range	1.1–90 kW	0.75–375 kW
efficiency levels	Eff3 – standard	IE1 – standard efficiency
	Eff2 – improved efficiency	IE2 – high efficiency
	Eff1 – high efficiency	IE3 – premium efficiency
degree of protection	IP5X	all
timetable (Directive 640/2009)	1. from June 16 June 2011: motors shall not be less efficient than the IE2 level 2. from 1 January 2015: motors with a rated output of 7.5–375 kW shall not be less efficient than IE3, or shall meet IE2, if equipped with a variable speed drive 3. from 1 January 2017: all motors with a rated power of 0.75–375 kW shall not be less efficient than IE3, or shall meet IE2, if equipped with a variable speed drive	
observations	IE1 similar efficiency to Eff2 IE2 similar efficiency to Eff1 IE2 equivalent to NEMA Efficient EPAct IE3 equivalent to NEMA Premium	

equipment. They are electronically commutated motor drives, in which a solid state converter is controlled with position/speed feedback to match the electric power supplied to the motor load requirements. These motor drives are: brushless DC motor drives, synchronous permanent magnet motor drives [5], synchronous reluctance motor drives and switched reluctance motor (SRM) drives. Among these, SRM drives are staking their claim in the market, because of their simple and robust construction, their fault-tolerance capability and their high efficiency. Since the renaissance experienced by SRM drives in the early 1980s [6], much research effort has been done to compare performances of SRM drives and IM drives. These comparisons have been performed based on different premises: same fixed output power [7], same frame [8] or same rated torque and speed under identical cooling conditions [9]. All authors have agreed that SRM drive offers significant benefits in efficiency, torque capability and power devices ratings, although at considerably higher acoustic noise.

Regulation 640/2009, the fast development of the technology in power electronics and electric drives and the increase of citizen awareness are important steps to push environmental studies, not just energy savings, in electric drives and to promote a new research field. This paper deals about the environmental impact and life cycle analysis of one SRM drive and two IM drives. It extends previous research conducted by the authors on the environmental impact of SRM drives, and on comparison of SRM and IM drives in environmental terms [10, 11]. It contains more critical reasoning regarding the bases of comparison between the two drive types, and considers EC Regulation 640/2009. The environmental impact and LCC were evaluated according to MEEUP methodology and taking into account different operating conditions.

This paper is organised as follows. Firstly, MEEUP methodology is briefly explained in Section 2. Then, the electric drives evaluated in the work are described in Section 3. The environmental impact and LCC of each drive are presented in Section 4. Finally, the conclusions are presented in Section 5.

2 MEEUP methodology

The MEEUP [12] was developed by VHK Consultants in Delft, Netherlands, on request from de EC. It is based on European regulations, and is designed for assessment of the environmental impact of energy using products in function of their production, distribution, use, recycling and waste disposal. The methodology should follow, not precede current environmental guidelines established in international treaties and enacted in appropriate EU legislation. The tools for assessing the environmental impact were based on accepted scientific principles and the data were collected from industry associations, EC reports and environmental studies from companies. MEEUP methodology is a simple method implemented in a spreadsheet that comprises the following parts: inputs, results and LCC.

For a given product, MEEUP analysis requires these inputs:

- bill of materials and manufacturing processes;
- performance, consumption and emission characteristics during the use phase;
- distribution characteristics: volume of package final product, transport mix;
- end-of-life characteristics: recycling and waste disposal.

The results are presented as a list of environmental indicators:

- energy, water (process and cooling);
- waste (hazardous and non-hazardous);
- global warming potential (GWP);
- acidification potential;
- volatile organic compounds (VOC);
- persistent organic pollutants (POP);
- heavy metals (to air and water);
- polycyclic aromatic hydrocarbons (PAH);
- particulate matter (PM);
- eutrophication potential of certain emissions to water (EP);
- ozone depletion potential.

The LCC considers all costs associated with the product: acquisition and installation costs; energy costs in the use phase; and repair and maintenance costs.

In the field of electric motors, MEEUP methodology has been used in the report for the EC: 'EUP lot 11 Motors', led by Dr A.T. de Almeida (University of Coimbra) [3].

3 Description of the drives

This paper focuses on environmental and LCC analysis of one SRM drive and two inverter-fed IM drives. Although SRM and IM are stator-magnetised motors, they have different constitution, whereas IM has a stator winding distributed in slots and a squirrel cage rotor, the SRM has a salient pole stator with concentrated windings and a salient pole rotor with no conductors or permanent magnets. An adequate indicator to compare different types of electrical machines is the torque per unit rotor volume that depends on the product of electric load and magnetic load. The magnetic load of SRM is lower than IM because of its salient pole structure. However its electric load is, generally, about twice that of IM. Therefore the torque per unit rotor volume of SRM is slightly higher than that of IM. To achieve the best comparison, the three motors were chosen with the same frame (IEC-90) and the drive systems were operated under the same conditions.

3.1 SRM drive

The SRM was an 8/6 SRM with 1.5 kW of output power and an IEC-90 frame (see Fig. 1). SRM voltage, 300 V, was selected in order to match with common three-phase network of 230 V (line voltage) for better comparison with induction motor of 230/400 V. SRM was designed using the well-known FLUX 2D Finite Element package [13]; a sample of the design process is illustrated in Fig. 2, which shows flux plots in aligned and unaligned positions. Moreover, several ecodesign criteria were also considered during its design:

- the amount of materials should be minimised;
- the number of non-recyclable parts (i.e. plastics) should be minimised;
- the motor should be easy to assemble and disassemble;
- the windings should be easy to remove.

The SRM was built by the authors, but has not yet been commercialised.

Fig. 1 *Photograph of the 8/6 SRM disassembled*

The SRM was controlled using the drive depicted in Fig. 3. The power converter is a four-phase, half asymmetric bridge (i.e. a classic converter), with two insulated gate bipolar transistors (IGBTs) and two fast diodes per phase. The rotor position is determined using an encoder or an ensemble comprising a slotted disk and three opto-interrupters placed inside the SRM. The speed controller, a proportional–integral controller, generates a current command based on the error between the reference speed and the motor speed. The current in the appropriate phase is regulated at the reference current by hysteresis control. The firing angle calculator computes the turn-on and turn-off angles at every instant, accounting for the speed and reference current at the instant. The authors must point out that neither the SRM nor its controller were built to optimal efficiency.

3.2 Inverter-fed IM motors

The IMs had four poles, 230/400 V, 1.5 kW of output power and IEC-90 frame. The first was an Eff3, and the second an Eff1/IE2 (for more details, see the Appendix). Both motors were driven by an inverter-fed vector control in closed loop through an incremental encoder. The IMs and the vector-control equipment were commercially available. The Eff3 IM was chosen to better appreciate the reduction in environmental impact obtained upon application of

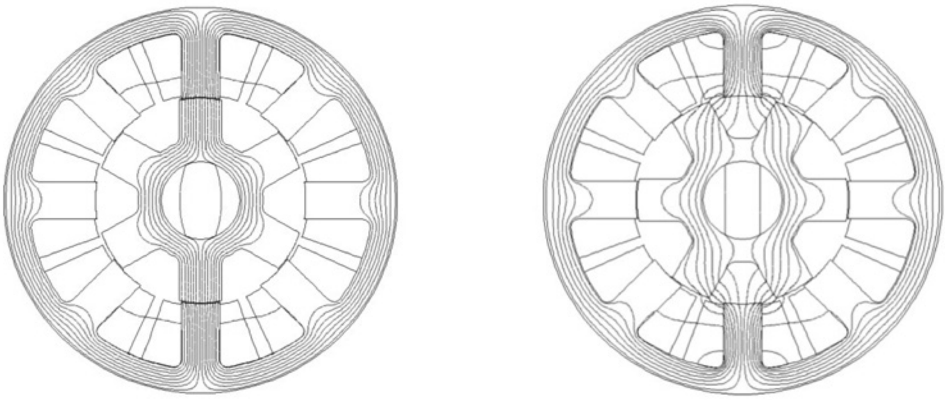

Fig. 2 *Flux plots of the 8/6 SRM in aligned (left) and unaligned (right) positions, obtained using the FLUX 2D FEM package*

doi: 10.1049/iet-epa.2011.0320

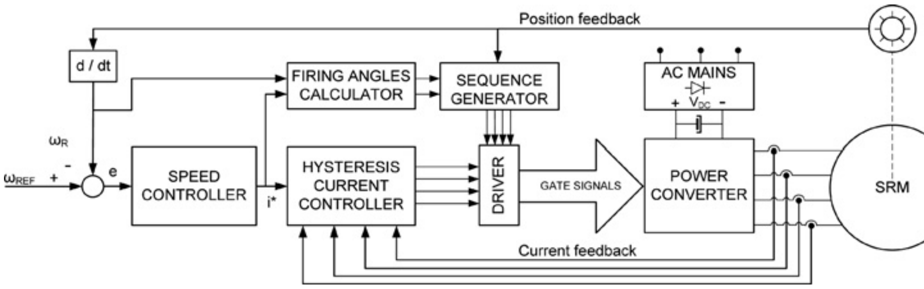

Fig. 3 *Schematic diagram of the SRM drive*

Regulation 640/2009. In contrast, the Eff1/IE2 IM was chosen because this type is expected to become the standard for IM drives in the European market within a few years [14].

3.3 Measuring efficiency

A DC motor coupled to a torque transducer was used to load the three drives. Global efficiency, ratio of mechanical power output to mains electrical power (including all the losses in the power converter stage), was determined for all drives. The input power (electrical power) was measured using a digital wattmeter (ZES Zimmer model LMG-450 four channels) and the output torque and speed by means of a torque transducer (HBM model T-34-10). The accuracy in per cent of the wattmeter is of 0.1% and the accuracy of torque and speed are of 0.1% for each ones. Therefore the accuracy of efficiency calculated by means of the quotient between mechanical power, product of torque (N m) per speed (rad/s) and electrical power is of 0.3%. This is a good accuracy that will have no influence in the results of LCC. For each, drive torque was plotted against global efficiency at different speeds: see Fig. 4 for the SRM drive; Fig. 5 for the Eff1/IE2 IM drive and Fig. 6, for the Eff3 IM drive.

4 Environmental impact and LCC

The environmental impact and LCC of the three studied drives were evaluated using MEEUP methodology. This section first covers the study data (inputs), which were collected including materials, energy use and economic data for each life stage and for each drive. Translation of these inputs into quantifiable environmental impacts is then discussed. Subsequently, to complete the environmental study, an analysis of the noise level of the different drives is also performed. Finally, an evaluation of the LCC related with the drives is presented.

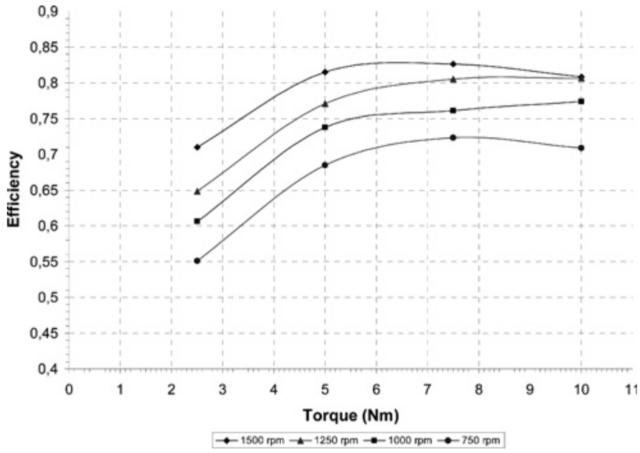

Fig. 5 *Global efficiency against torque for the Eff1/IE2 IM drive*

4.1 Inputs

The material composition of the drives, based on the bill of materials (including packaging), is listed in Table 2. The content of materials is a key issue in the analysis of LCC and it depends on the type of drive. Consequently, given the different constitution of the drives studied and in order to better understand the final results, it is appropriate to briefly analyse the values of Table 2. Although the motor

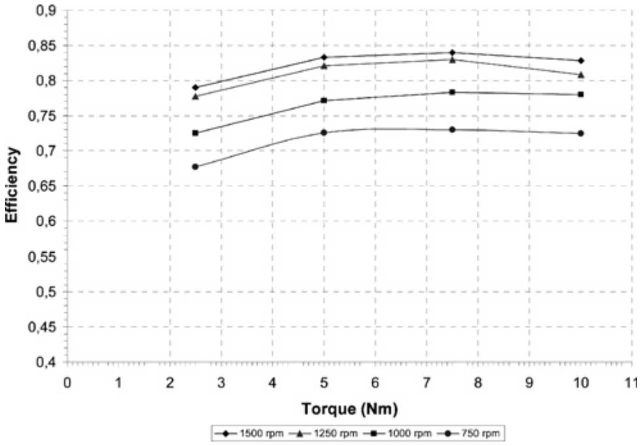

Fig. 4 *Global efficiency against torque for the SRM drive*

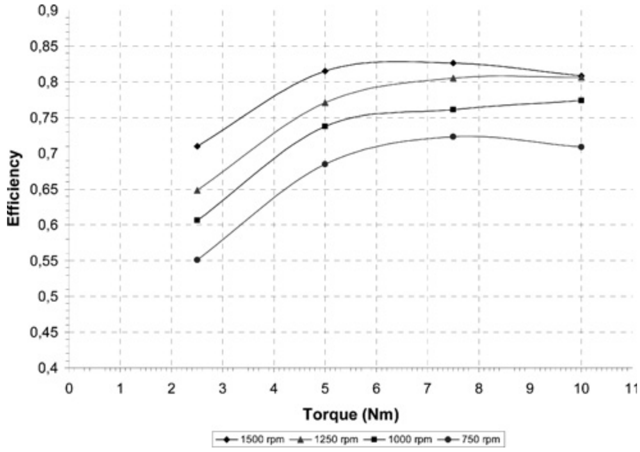

Fig. 6 *Global efficiency against torque for the Eff3 IM drive*

Table 2 Bill of materials of each drive

Material, kg	Eff3 IM	Eff1/IE2 IM	8/6 SRM
electrical steel	7.84	8.65	7.46
other steel	2.18	1.73	1.51
aluminium	5.13	5.28	4.48
copper	1.80	2.05	2.50
insulation material	0.07	0.07	0.01
impregnation resin	0.44	0.44	0.20
paint	0.06	0.06	0.06
plastics	0.39	0.39	0.56
electronics	0.29	0.29	0.42
packing material	1.50	1.50	1.50

case is of aluminium in the three motors, aluminium weight is higher in IMs because of their squirrel cage rotor. Electric steel, insulation material and impregnation resin weight are higher in IMs as consequence of the small surface of the slots and their distributed stator winding. Instead, copper weight is higher in SRM because of its higher electric load. Plastics and electronics weight are also higher in SRM because its power converter has four phases and therefore requires more components.

In an attempt to mimic the real behaviour of the drives in their use phase, three cases with different operating conditions were considered. The lifetime, the number of operating hours, the load factor and the speed (with its corresponding efficiency) for each case have been compiled in Table 3.

4.2 Environmental impact

The environmental impacts in the production, distribution and end-of-life phase for each drive and for the different considered cases were calculated using the spreadsheet of MEEUP and they are shown in Table 4.

Table 5 lists the environmental impacts in the use phase for the three drives and Table 6 shows the total environmental impacts for the three studied cases. To better visualise the comparison of the environmental impact of each drive, some of their respective impacts were graphed for each set of operating conditions (see Figs. 7–9). These graphs show the normalised influence of eight leading environmental indicators for each drive, relative to Eff3 IM (assigned a

Table 3 Operating conditions in the use phase

Variable	Case 1	Case 2			Case 3	
Lifetime, years	12	12			12	
operating hours	4000	1000	1000	2000	2000	2000
load factor, %	75	50	100	75	75	75
speed, rpm	1500	1000	1000	1000	750	1250
efficiency IM (Eff3)	0.750	0.628	0.686	0.668	0.622	0.741
efficiency IM (Eff1/IE2)	0.826	0.737	0.774	0.761	0.723	0.805
efficiency 8/6 SRM	0.840	0.771	0.780	0.783	0.730	0.830

Table 4 Environmental impacts in the production, distribution and end-of-life phases for each drive

Main indicators	Production			Distribution	End-of-life		
	Eff3 IM	Eff1/IE2 IM	8/6 SRM	All the motors	Eff3 IM	Eff1/IE2 IM	8/6 SRM
total energy GER[a] (MJ)	1373	1452	1435	88	67	70	60
of which, electricity (in primary MJ)	292	301	314	0	−8	−8	−11
water process (l)	132	133	169	0	−7	−7	−10
water cooling (l)	368	372	290	0	−3	−3	−4
waste, non-hazardous landfill, g	57 011	63 246	69 483	69	1092	1138	1023
waste, hazardous incinerated, g	348	348	455	1	868	868	803
Emissions to air							
greenhouse gases in GWP100[b] (kg CO_2 eq)	86	91	88	7	5	6	5
acidification potential (g SO_2 eq)	937	1023	1174	19	8	9	5
VOC (g)[c]	3	3	3	1	0	0	0
POP (ng I-Teq)[d]	432	456	395	0	8	8	7
heavy metals (mg Ni eq)	222	243	266	4	33	34	31
PAHs (mg Ni eq)[e]	103	107	96	4	−1	−1	−1
particulate matter, g	74	77	70	93	158	161	147
Emissions to water							
heavy metals, mg Hg/20	80	85	82	0	6	6	4
eutrophication, g PO_4	8	8	6	0	1	1	0

[a] Gross energy requirement
[b] Global warming potential
[c] Volatile organic compounds
[d] Persistent organic pollutants
[e] Polycyclic aromatic hydrocarbon

Table 5 Environmental impact in the use phase for each drive

Main indicators	Case 1			Case 2			Case 3		
	Eff3 IM	Eff1/IE2IM	8/6 SRM	Eff3 IM	Eff1/IE2 IM	8/6 SRM	Eff3 IM	Eff1/IE2 IM	8/6 SRM
total energy GER$^{(a)}$ (MJ)	189 434	119 933	108 945	285 633	180 186	161 990	272 700	178 529	164 517
of which, electricity (in primary MJ)	188 701	119 199	108 212	283 433	177 984	159 790	271 234	177 061	163 050
water process (l)	12 581	7948	7216	18 899	11 869	10 657	18 085	11 806	10 873
water cooling (l)	503 198	317 860	288 560	755 810	474 612	426 090	723 282	472 155	434 790
waste, non-hazardous landfill, g	219 355	138 834	126 157	330 326	208 251	187 341	315 614	206 551	190 430
waste, hazardous incinerated, g	4352	2750	2498	6541	4112	3695	6257	4087	3766
Emissions to air									
Greenhouse gases in GWP100$^{(b)}$ (kg CO$_2$ eq)	8291	5258	4779	12 539	7937	7143	11 950	7840	7229
acidification potential, g SO$_2$ eq	48 655	30 759	27 931	73 177	46 027	41 346	69 972	45 724	42 119
VOC, g$^{(c)}$	83	57	52	142	102	95	126	90	85
POP, ng I-Teq$^{(d)}$	1241	786	713	1871	1180	1059	1786	1170	1077
heavy metals, mg Ni eq	3396	2203	2015	5337	3529	3217	4970	3354	3115
PAHs, mg Ni eq$^{(e)}$	529	392	370	1029	822	786	848	663	635
particulate matter, g	3685	3302	3242	9499	8919	8819	6785	6267	6190
Emissions to water									
heavy metals, mg Hg/20	1217	769	699	1830	1150	1033	1750	1143	1053
eutrophication, g PO$_4$	6	4	3	9	6	5	9	6	5

Table 6 Environmental impacts for each drive (total)

Main indicators	Case 1			Case 2			Case 3		
	Eff3 IM	Eff1/IE2IM	8/6 SRM	Eff3 IM	Eff1/IE2IM	8/6 SRM	Eff3 IM	Eff1/IE2 IM	8/6 SRM
total energy GER$^{(a)}$ (MJ)	190 962	121 543	110 528	287 161	181 796	163 573	274 228	180 139	166 100
of which, electricity (in primary MJ)	188 984	119 492	108 516	283 717	178 277	160 094	271 517	177 354	163 354
water process (l)	12 706	8073	7375	19024	11 994	10 816	18 210	11 932	11 032
water cooling (l)	503 563	318 229	288 846	756 175	474 981	426 377	723 647	472 524	435 076
waste, non-hazardous landfill, g	277 526	203 287	196 732	388 498	272 704	257 916	373 786	271 004	261 005
waste, hazardous incinerated, g	5569	3968	3757	7759	5329	4954	7474	5305	5025
Emissions to air									
greenhouse gases in GWP100,$^{(b)}$ kg CO$_2$ eq	8389	5362	4879	12 636	8040	7243	12 048	7944	7328
acidification potential, g SO$_2$ eq	49 618	31 810	29 130	74 141	47 077	42 545	70 935	46 774	43 317
VOC, g$^{(c)}$	86	60	56	145	106	99	129	94	88
POP, ng I-Teq$^{(d)}$	1681	1250	1115	2311	1644	1461	2226	1634	1479
heavy metals, mg Ni eq	3654	2484	2316	5596	3809	3518	5228	3635	3415
PAHs, mg Ni eq$^{(e)}$	635	502	469	1136	932	885	955	773	734
particulate matter, g	4008	3633	3552	9823	9250	9129	7109	6598	6500
Emissions to water									
heavy metals, mg Hg/20	1304	861	784	1916	1241	1118	1837	1234	1138
eutrophication, g PO$_4$	14	12	10	17	14	11	17	14	11

value of 1). These eight environmental indicators were: total energy (GER), water (process), water non-hazardous landfill, greenhouse gases in GWP100, acidification emissions, heavy metals, PM and eutrophication.

4.3 Analysis of noise level

Although noise is not an environmental indicator in MEEUP methodology, it seems appropriate to carry out an analysis of the noise level in the considered drives. The average sound power (L_{wA}) and the average sound pressure (L_{pA}) were measured in full load conditions (load factor 100%) and 1500 rpm for the three drives, the results obtained are listed in Table 7. The average sound pressure was measured at 1 m of distance from the machine surface.

4.4 Life cycle costs

Table 8 summarises the LCC for each drive. LCC, according to MEEUP methodology, is the sum of purchase and installation costs; energy costs in the use phase; and repair and maintenance costs. The energy costs in the use phase are electrical energy costs. The electric drives are not end-use devices; they are energy converters thus only the energy because of losses is consumed inside the drive therefore only this energy must be considered in the LCC, the rest of the absorbed energy is transformed into mechanical power. The electrical energy costs were calculated based on current electricity rates in Spain. The product list price for each IM drive (including the costs of motor, vector control equipment and encoder) is considered, whereas that of the SRM drive is just an estimate. The repair and maintenance

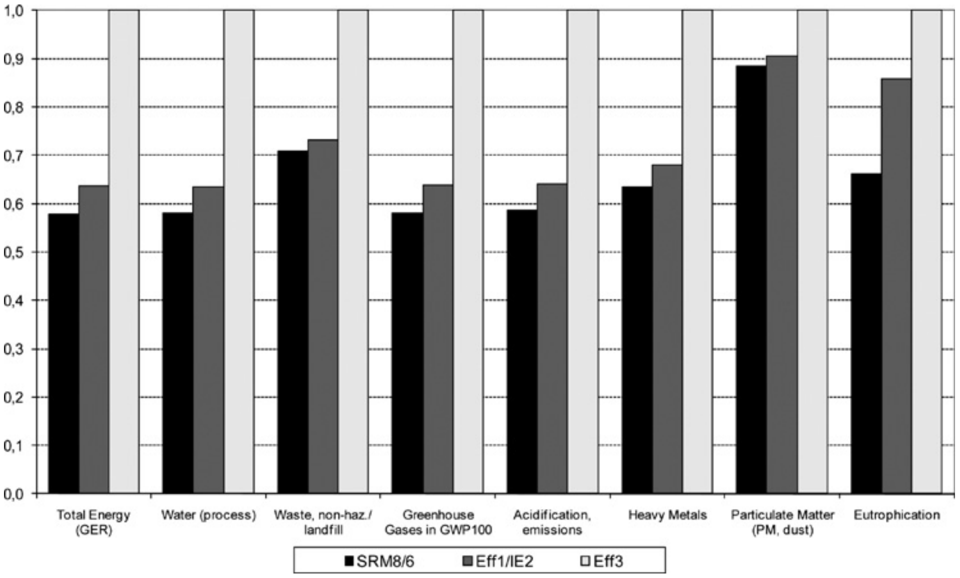

Fig. 7 *Graph of eight major environmental impacts for each drive in case 1 (values normalised to those of Eff3 IM, set at 1)*

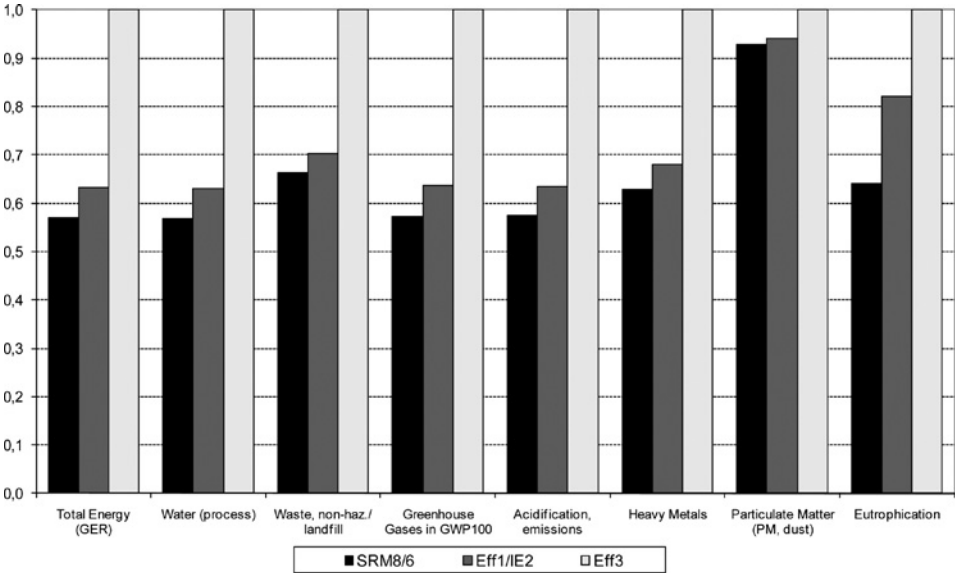

Fig. 8 *Graph of eight major environmental impacts for each drive in case 2 (values normalised to those of Eff3 IM, set at 1)*

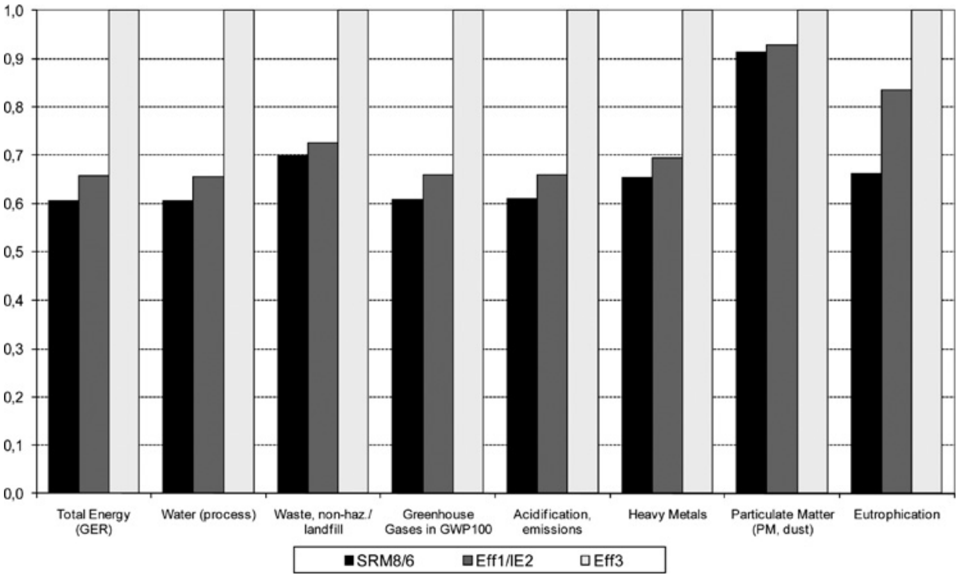

Fig. 9 *Graph of eight major environmental impacts for each drive in case 3 (values normalised to those of Eff3 IM, set at 1)*

doi: 10.1049/iet-epa.2011.0320

Table 7 Average sound power (L_{wA}) and the average sound pressure (L_{pA}) of the three drives

	L_{wA}, dB(A)	L_{pA}, dB(A)
Eff3 IM	84	73
Eff1/IE2 IM	88	77
8/6 SRM	100	89

Table 8 Life cycle costs

	Eff3 IM	Eff1/IE2 IM	8/6 SRM
product list price, €	1281	1425	1542
energy costs, €			
case 1	1982	1252	1137
case 2	2978	1870	1679
case 3	2849	1860	1713
repair and maintenance costs	–	–	–
life cycle cost LCC, €			
case 1	3263	2677	2679
case 2	4259	3295	3221
sase 3	4130	3285	3255

costs were considered negligible because drives having a power of 5 kW or less are not typically repaired upon failure.

For a better comparison between machines with different efficiencies and different initial costs, payback period (PP) and net present value (NPV) were determined, Table 9. Both terms were calculated for the Eff1/IE2 IM drive and 8/6 SRM drive against the Eff3 IM drive for the different cases considered. It is important to point out that the per year energy savings (first two columns of Table 9) were computed by means of the values of Table 3, considering the difference between the cost of absorbed electrical energy of the drives in comparison at each case. The NPV was obtained in all the cases with a discount rate of 4% and considering a period of time equal to the lifetime of the drives, 12 years.

4.5 Discussion

As indicated by Table 4, in the production phase, the SRM drive scores higher in all the environmental indicators than do the IM drives, whereas in the end-of-life phase, the opposite is true for most of the indicators (except electricity, water process and water cooling); obviously, in the distribution phase, the drives all score equally. Better results for the SRM could surely have been obtained if a three-phase SRM had been evaluated instead of a four-phase one, as it would require less electronics components and plastics.

Table 5 shows the environmental impacts in the use phase, in which the SRM drive scores better than both IM drives in all the three cases considered. This is due to its superior efficiency in all the ranges, especially at light loads. As corroborated by the overall results compiled in Table 6 and in Figs. 7–9, the SRM drive shows lower environmental impact than the considered IM drives in all the studied cases. The noise analysis confirms what is well known, SRM drive is noisier than IM drives. Furthermore, the LCC analysis indicates that the SRM drive has lower electricity costs in all cases. However, its total costs are not as favourable, even in case 1, the Eff1/IE2 IM drive implies lower costs, because of SRM drives have not yet become the status of standard commodity, and therefore have a higher list price. One of the main reasons for this fact is the lack of specific power modules for SRM. In this sense, it is not surprising that the PP of SRM drives is longer, for all the cases, than those of Eff1/IE2 IM drives. Nevertheless, it is well known that simple payback calculation, PP, ignores the value of money and therefore if it has to be taken into account NPV is a better indicator. Table 8 shows that the values of NPV are clearly in favour of SRM drive except for the case 1.

It could argue that if an IE3 IM had been evaluated in this study, it would have shown better results than the SRM in environmental terms. However, in that case, for a fair comparison, a SRM drive with optimised efficiency would have to be used.

This study was carried out using MEEUP methodology, which has proven to be a simple methodology that gives good results, especially for the use phase. One drawback of MEEUP methodology is that it does not reflect very well some of the main advantages of SRM drives, namely, the ease of disassembly in the end-of-life phase.

In this investigation the drives considered were rated at 1.5 kW of output power that can be considered representative of the low power range. Further studies should be carried out in drives of medium and high power in order to complete this research.

5 Conclusion

The environmental impacts and LCC of one SRM drive and two inverter-fed IM drives have been analysed. This study takes into account EC Regulation 640/2009, and was performed using MEEUP methodology, considering different operating conditions. In all the studied cases, the SRM drive shows lower environmental impact than do the IM drives. Therefore lower environmental impact is yet another feature to add to the list of advantages of SRM drives, and should be considered when comparing SRM and IM drives.

Table 9 Payback period and net present value

	Energy savings Eff1/IE2 IM against Eff3 IM, kWh/year	Energy savings 8/6 SRM against Eff3 IM, kWh/year	PP Eff1/IE2 IM against Eff3 IM, years	PP 8/6 SRM against Eff3 IM, years	NPV Eff1/IE2 IM against Eff3 IM, €	NPV 8/6 SRM against Eff3 IM, €
case 1	552	639	2.1	3.3	504	489
case 2	837	981	1.4	2.1	839	892
case 3	748	857	1.5	2.4	734	747

6 Acknowledgments

This research was supported by the Spanish Ministry of Education and Science and the ERDF (DPI2006-09880).

7 References

1 ‘Key world energy statistics’ (International Energy Agency, 2010)

2 Binder, A.: ‘Potentials for energy savings with modern drive technology: a survey’. SPEDAM, 2008, pp. 90–95

3 de Almeida, A.T., Ferreira, F.J.T.E., Fong, J., Fonseca, P.: ‘EUP Lot 11 motors: final’. February 2008

4 Commission Regulation (EC) No. 640/2009 of 27 July 2009 implementing Directive 2005/327 EC of the European Parliament and of the Council with regard to ecodesign requirements for electric motors. Official Journal of the European Union; 23.7.2009

5 de Ameida, A.T., Ferreira, F.J.T.E., Fong, J.A.C.: ‘Standards for efficiency of electric motors, permanent magnet synchronous motor technology’, *IEEE Ind. Appl. Mag.*, 2011, **17**, (1), pp. 12–19

6 Lawrenson, P.J., Stephenson, J.M., Blenkinsop, P.T., Corda, J., Fulton, N.N.: ‘Variable speed switched reluctance motors’. Proc. IEE, July 1980, vol. 127, pt. B, no 4, pp. 253–265

7 Mogbelli, H., Adams, G.E., Hoft, R.G.: ‘Performance of a 10-HP switched reluctance motor and comparison with induction motor’, *IEEE Trans. Ind. Appl.*, 1991, **27**, (3), pp. 531–538

8 Turner, M.J., Young, P.Y.P., Wallace, R.S.: ‘Comparing European 132 frame switched reluctance and induction motor drives’, *IECON*, 1997, **2**, pp. 403–408

9 Binder, A.: ‘Switched reluctance drive and inverter-fed induction machine: a comparison of design parameters and drive performance’, *Electr. Eng*, 2000, **82**, pp. 239–248

10 Martínez, E., Andrada, P., Blanqué, B., Torrent, M., Perat, J.I., Sánchez, J.A.: ‘Environmental and life cycle cost analysis of a switched reluctance motor’. ICEM 2008, CD-ROM, 6–9 September 2008 Vilamoura, Portugal

11 Andrada, P., Blanqué, B., Martínez, E., Perat, J.I., Sánchez, J.A., Torrent, M.: ‘Comparison of environmental and life cycle impact of a switched reluctance motor drive and inverter-fed induction motor drives’. Int. Conf. Renewable Energies and Power Quality (ICREPQ’09), Valencia, Spain, 15–17 April 2009

12 MEEUP Methodology report, Final 2005, VHK for European Commission. ec.europa.eu/energy/demand/…/2005_11_28_final report1_en.pdf

13 FLUX User’s manual. www.cedrat.com

14 Jardot, D., Eichhammer, W., Fleiter, T.: ‘Effects of economies of scale and experience on the costs of energy-efficient technologies- case of study of electric motors in Germany’, *Energy Efficiency*, 2010, **3**, pp. 331–346

8 Appendix

SRM and IMs nameplate data are shown in Table 10.

Main data for vector control equipment:

PDL electronics
Microdrive Elite ME-6.5
Closed loop vector control
Input voltage: 230 Vac 3 phase
Frequency range: 0–100 Hz
Efficiency (full load, 50 Hz): >97%
Output current: 6.5 A
Insulation class: IP54

Table 10 SRM and IMs nameplate data

	8/6 SRM	Eff3 IM	Eff1/IE2 IM
frame size	90 L	90 L	90 L
power, kW	1.5	1.5	1.5
speed, rpm	1500	1420	1440
voltage	300 V DC[a]	230/400 V	230/400 V
current, A	5,8[b]	6.1/3.5	5.7/3.3
power factor	–	0.8	0.77
IP	IP55	IP55	IP55
insulation class	F	F	F

[a] 230 V AC mains

[b] RMS value, hysteresis control

doi: 10.1049/iet-epa.2011.0320