Applied GIS

ISSN: 1832-5505
Vol-09, Issue-04 Oct 2021

One switching reluctance motor drive and two inverter-fed induction motor drives were compared in terms of environmental impact and total life cycle cost

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Abstract:

Two inverter-fed induction motor (IM) drives and one switching reluctance motor (SRM) drive are compared in terms of their environmental impact and LCC. We use critical thinking to analyse the two drive kinds, and we take into account the European Commission's (EC) Regulation 640/2009. The environmental effect and LCC were calculated taking into consideration various operational scenarios and the Methodology for the Eco-design of Energy-Using Products. Researchers observed that the SRM drive had a less carbon footprint than the IM drives.

Introduction

In 2008, global primary energy consumption was 12.267 Mtoe per year. The vast majority of this power (81%) is generated by fossil fuels [1]. A rise in air pollution and a considerable contribution to global warming may be directly attributed to the unrestrained use of coal, oil, and natural gas. Thus, energy conservation programs are desperately required to halt the waste of fossil fuels and its repercussions. Most of the main energy we use is transformed into electricity. Electric motors use roughly two-thirds of the world's electrical energy in industrialized nations. In 2005, the usage phase energy consumption for electric motors in the European Union (EU) was 1067 TWh, which equated to 427 Mt of CO2 emissions [2]. Without restrictions on energy usage, it is expected that motor energy consumption during the use phase would rise to 1252 TWh by the year 2020. Therefore, improvements in electric motor efficiency are needed to provide these energy savings and pollution reductions. Minimum efficiency regulations for electric motors have been established in the United States, Canada, Australia, and most recently the European Union. Electric motors with greater efficiencies (premium efficiency motors) have been categorized by many organizations, the most prominent of which being the National Electrical Manufacturers Association (NEMA).

Given the European setting of this paper, the authors thought it would be appropriate to provide a quick overview of EU regulation of electric motor efficiency. Based on testing procedures and limits of acceptance defined in IEC 60034-2: 1996 [3], the current European efficiency standards 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). Energy efficiency standards for electric motors and variable speed drives are set by Regulation (EC) No. 640/2009 [4], which is in turn based on Directive (EC) No. 2005/32/EC. Based on

the methods of testing and the tolerance levels specified in IEC 60034-2-1:2007, new efficiency standards have recently been set in standard IEC 60034-30:2008. Timelines for implementing the CEMEP/EU agreement's eco-design standards for electric motors are laid forth in Table 1.

The MEEUP approach VHK

Consultants of Delft, Netherlands, was commissioned by the EC to create the MEEUP [12]. It is based on European legislation and is meant to evaluate the environmental effects of energy-intensive items over the whole product life cycle, from manufacturing to consumer use to final disposal. Current environmental principles set by international treaties and incorporated in relevant EU legislation should serve as a basis for the process, not a precedent. Data was gathered from trade groups, EC reports, and company environmental studies; assessment techniques were based on established scientific concepts. Inputs, outputs, and LCC make up the three main sections of the straightforward spreadsheet-based MEEUP technique. These are the inputs needed for a MEEUP analysis: bill of materials and manufacturing processes; performance, consumption, and emission characteristics during the use phase; distribution characteristics: volume of packaged final product, transport mix; end-of-life characteristics: recycling and waste disposal. The findings are given in the form of a catalogue of ecological metrics: 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), and ozone depletion potential are all factors to consider.

Acquisition and setup fees, energy expenses during usage, and repair and maintenance are all included into the LCC. Dr. A.T. de Almeida (University of Coimbra) headed the team that wrote the report for the European Commission (EC) titled "EUP lot 11 Motors," which made use of MEEUP methodology in the context of electric motors [3].

Drives, Part 3: A Description

The environmental and life cycle cost (LCC) analyses of one SRM drive and two inverter-fed IM drives are shown here. Although both the SRM and IM are stator-magnetized motors, their construction is distinct. The IM has a stator winding dispersed in slots and a squirrel cage rotor, whereas the SRM has a salient pole stator with concentrated windings and a salient pole rotor that does not need conductors or permanent magnets. Torque per unit rotor volume, which is dependent on the product of electric load and magnetic load, is a good metric to use when comparing various kinds of electrical machines. Because of its distinctive pole structure, SRM has a lower magnetic load than IM. However, it uses almost twice as much electricity as IM. This means , SRM produces somewhat more torque than IM per unit of rotor volume. All three motors had the same frame (IEC-90) and were run on identical driving systems for an accurate comparison.

Propulsion through SRM

As can be seen in Fig. 1, the SRM in question was an 8/6 SRM with an output power of 1.5 kW and an IEC-90 frame. The 300 V SRM voltage was chosen so that it would be comparable to the 230 V (line voltage) of a standard three-phase network and the 230 V (400 V) of an induction motor. The popular FLUX 2D Finite Element program [13] was used in the design of SRM; an example of the design process is shown in Fig. 2, which compares aligned and unaligned flux plots. The design process also took into account numerous eco-design objectives, such as: reducing the quantity of materials used; reducing the number of non-recyclable components (i.e., plastics); making the motor simple to build and dismantle; and making the windings simple to remove. The writers constructed the SRM, but it has not yet been released to the public.

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.

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

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ISSN: 1832-5505

Vol-09, Issue-04 Oct 2021

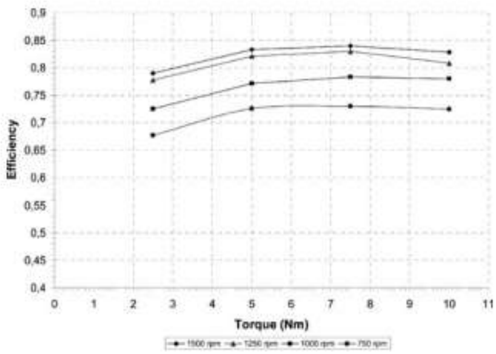

Fig. 2Global efficiency against torque for the SRM drive

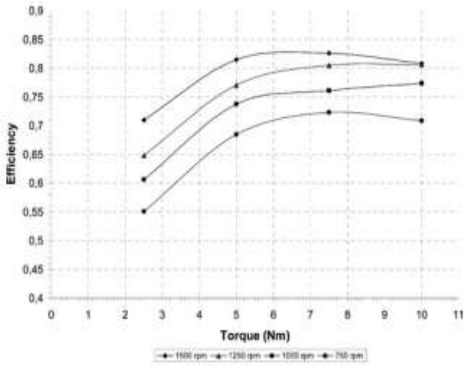

Fig. 3 Global efficiency against torque for the Eff1/IE2 IM drive

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.

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

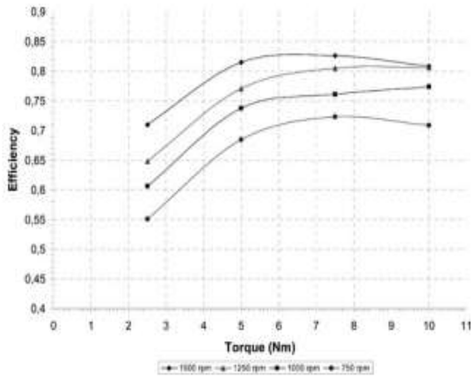

Fig. 4Global efficiency against torque for the Eff3 IM drive

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

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)	0.758	0.629	0.686	0.688	0.622	0.741
efficiency IM (Eff1/IE2)	0.826	0.737	0.774	0.761	0.723	0.806
efficiency 8/6 SRM	0.840	0.771	0.790	0.783	0.730	0.838

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

ISSN: 1832-5505
Vol-09, Issue-04 Oct 2021

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	1436	88	67	70	60
of which, electricity (in primary MJ)	292	301	314	0	−9	−8	−11
water process (l)	132	133	169	0	−7	−7	−10
water cooling (l)	388	372	290	0	−3	−3	−4
waste, non-hazardous landfill, g	57 011	63 246	69 463	88	1092	1136	1023
waste, hazardous incinerated, g	340	340	458	1	860	892	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	16	8	8	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	288	4	33	34	31
PAHs (mg Ni eq)[e]	103	107	96	4	−1	−1	−1
particulate matter, g	74	77	73	93	158	161	147
Emissions to water							
heavy metals, mg Hg/20	90	85	82	0	6	6	4
eutrophication, g PO_4	9	9	6	0	1	1	0

Discussion

Table 4 shows that during production, the SRM drive outperforms the IM drives in every environmental indicator, while during disposal, the opposite is true for most indicators (except electricity, water process, and water cooling). During distribution, the drives perform similarly. A three-phase SRM, which uses fewer electronic parts and plastics, would likely have yielded better results than a four-phase SRM, which was studied. The environmental implications during the usage phase are shown in Table 5, where the SRM drive outperforms the IM drives in all three scenarios. This is because it has higher efficiency across the board, particularly under low loads. Table 6 and Figures 7-9 indicate that, generally, the SRM drive has a less negative effect on the environment compared to the evaluated IM drives. The examination of the noise levels corroborates the common knowledge that SRM drives are louder than IM drives. The SRM drive also has reduced power costs across the board, as shown by the LCC study. SRM drives have not yet reached the level of standard commodity, therefore their list price is greater, making them more expensive overall, even in instance 1, where the Eff1/ IE2 IM drive suggests reduced costs. This is mostly due to the unavailability of dedicated power modules for SRM. As a result, it should come as no surprise that SRM drives have a consistently longer PP than Eff1/IE2 IM drives. However, it is generally recognized that a basic payback calculation, PP, does not take into account the value of money, thus NPV is a superior indication if it must be considered. Except for Case 1, the NPV values in Table 8 strongly favour SRM drive. One might make the case that the IE3 IM would have performed better environmentally if tested alongside the SRM in this research. However, in that instance, an SRM drive with optimized efficiency would be required for an accurate comparison. The MEEUP technique was used for this research since it has been shown to be a straightforward approach that yields useful outcomes, particularly at the implementation stage. However, the simplicity of disassembly at the end-of-life phase is one of the primary benefits of SRM drives that is not well reflected in MEEUP. The output power of the drives studied in this analysis was 1.5 kW, which is typical for drives in the low power range. In order to finish this study, further research has to be done on drives with medium and high power.

Conclusion

We have compared the LCC and environmental effects of one SRM drive to those of two inverter-fed IM drives. This analysis was conducted using MEEUP methodology and took into consideration a variety of operational settings to ensure compliance with EC Regulation 640/2009. The SRM drive has a smaller footprint than the IM drives in all scenarios. Therefore, while comparing SRM and IM drives, it is important to take into account the former's reduced environmental effect.

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ISSN: 1832-5505
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