Eliminating rare earth permanent magnets on low-speed high-torque machines: A performance and cost comparison of synchronous reluctance machines, ferrite permanent magnet-synchronous reluctance machines and permanent magnet synchronous machines for a direct-drive elevator system

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Abstract

In the last few years, the reduction of the dependency on rare-earth magnets has been one of the main concerns for electrical machine manufacturers. Synchronous reluctance machines (SynRMs) and ferrite permanent magnet-assisted synchronous reluctance machines (PMa-SynRMs) are emerging as alternatives to permanent magnet synchronous machines (PMSMs) in several applications. In low-speed high-torque applications, PMSMs with large amounts of rare-earth magnets are commonly employed. Thus, it is of particular interest to replace PMSMs by SynRMs or PMa-SynRMs. This article studies the feasibility of using SynRMs and ferrite PMa-SynRMs for a direct-drive elevator system. The challenge lies in obtaining performance characteristics comparable to those of PMSMs, but without resorting to the use of rare-earth permanent magnets. The main criteria for designing SynRMs and PMa-SynRMs for low-speed high-torque applications are presented. Afterwards, a SynRM and a ferrite PMa-SynRM are designed for 160 rpm 200 Nm rated conditions, and a performance and cost comparison between these machines and a commercial PMSM is conducted.

1 | INTRODUCTION

Permanent magnet synchronous machines (PMSMs) are the most widely used machines for low-speed high-torque applications. They exhibit a high torque density capability, at the expense of needing large amounts of rare-earth permanent magnets.

However, concerns regarding rare-earth scarcity, price fluctuations, supply shortage, environmental and social impact have increased the interest in other technologies. Among them, the synchronous reluctance machine (SynRM) and the ferrite permanent magnet-assisted synchronous reluctance machine (PMa-SynRM) arise as promising alternatives.

Several authors have made comparative studies among PMSMs, SynRMs and PMa-SynRMs, and have concluded that PMSMs obtain better performance characteristics compared with SynRMs and even PMa-SynRMs [1–4]. However, SynRMs and PMa-SynRMs outperform the former in terms of: lower price [5], less stringent constraints on the rotor temperature, better fault-tolerant behaviour etc. A summary of the conclusions drawn from previous studies is shown in Tables 1 and 2.

In some applications such as traction or industry, SynRMs and PMa-SynRMs have been deemed a viable alternative for PMSMs [1,6–9]. Some of the major electric motor manufacturers offer SynRMs working in the range of 1000–3000 rpm and 0.55–315 kW in their catalogues. Nevertheless, no examples of low-speed reluctance machines can be found in the market.

Replacing PMSMs by SynRMs or ferrite PMa-SynRMs in low-speed high-torque applications is especially interesting due...
TABLE 1 SynRMs’ characteristics compared with PMSMs’

| Advantages                          | Disadvantages                        |
|------------------------------------|--------------------------------------|
| • Lower price.                     | • Slightly lower torque density.     |
| • Higher rotor temperature capability. | • Slightly lower power factor.       |
| • Slightly lower efficiency.       | • Poorer efficiency.                 |

TABLE 2 PMa-SynRMs’ characteristics compared with PMSMs’

| Advantages                          | Disadvantages                        |
|------------------------------------|--------------------------------------|
| • Significantly lower price.        | • Significantly lower torque density.|
| • No demagnetisation risk.          | • Significantly lower power factor.  |
| • No rotor temperature restriction. | • Poorer efficiency.                 |
| • No voltage or currents induced when a fault occurs. | |

Figure 1 Material cost comparison between SynRM, PMSM and PMa-SynRM [5]. PMa-SynRM, permanent Magnet magnet-assisted synchronous reluctance machines; PMSM, permanent magnet synchronous machines; SynRM, synchronous reluctance machines.

to their high rare-earth permanent magnet content. Eliminating the expensive magnet material can produce a significant cost reduction, as shown in Figure 1 [5]. At the same time, it is challenging to obtain performance characteristics comparable to those of the PMSMs without resorting to the use of rare-earth permanent magnets.

The objective of this article is to study the feasibility of using SynRMs and PMa-SynRMs for low-speed high-torque applications, with special focus on motor cost and performance. For that purpose, first a design methodology for SynRMs and PMa-SynRMs is outlined; next, applying the proposed methodology, two machines are designed so that their performances and costs are compared with those of a real lifting application involving 200 Nm 160 rpm PMSM.

This article is organised as follows: first the procedure employed to calculate the performance characteristics of SynRMs and PMa-SynRMs is presented in Section 2. In Section 3, the specifications of the designed machines are detailed. In Section 4, the main design criteria for low-speed high-torque applications are outlined. In Sections 5 and 6, a SynRM and a PMa-SynRM are designed and evaluated respectively, and their simulation results are compared with those of a PMSM. Finally, the main conclusions of the study are discussed in Section 7.

2 | SynRM AND PMA-SYNRM PERFORMANCE EVALUATION

In this section, the procedure used to calculate the performance characteristics of SynRMs and PMa-SynRMs is presented. The evaluation routine has been implemented in a tool developed in Matlab that allows to size and calculate machines quickly and automatically.

First, a complete design of the machine is defined (geometry, winding, material etc.) from the machine specifications, design restrictions and reference parameters (i.e. desired flux and current density values). Analytical formulas based on classical sizing equations are employed [10].

Once the machine is completely defined, its full performance characteristics are calculated. The calculation procedure works as follows: a parametrised model in an open source finite element software, FEMM, is generated; this model is evaluated via multi-static simulations to obtain the electromagnetic torque waveform, flux linkages and flux densities in various parts of the machine. An example of a SynRM design evaluated in FEMM is shown in Figure 2. The rest of performance characteristics are obtained by post-processing the FEA results through analytical formulas.

The temperatures in different parts of the machines are calculated as well in order to analyse the thermal behaviour of the different machines. For this purpose, the commercial software Motor-CAD has been used in this research work.

The proposed calculation procedure has proven accurate compared with experimental results. A detailed description of the proposed scheme and its validation by testing a prototype are presented in a previous article by the authors [11].

Additionally, an automatic optimisation tool for the optimisation of the rotor geometry has been developed. The optimisation method is based on the Multi-Objective Differential Evolution (MODE) algorithm, which is a common procedure for machine geometry optimisation [12–16].

The MODE algorithm optimises a problem by iteratively generating new individuals by recombination and mutation, trying to improve a candidate solution targeting a given performance requirement. In this specific case, the process begins with a simple rotor geometry and new machines with different rotor flux barriers are automatically created and evaluated. Figure 3 shows an example of an optimisation process. A point
cloud with thousands of single points is shown, where each one corresponds to the results (Average electromagnetic torque, $M_{em}$, and torque ripple, $M_{em,\text{ripple}}$) of an specific machine. The result of the optimisation process is the group of red points, which is the Pareto frontier, formed by the machines that obtain the best $M_{em}$-$M_{em,\text{ripple}}$ results.

3 | MACHINE SPECIFICATIONS

As previously mentioned, the objective of this article is to study the feasibility of SynRMs and PMa-SynRMs for low-speed high-torque applications. It has been decided to focus the study on a particular low-speed high-torque case: a 160 rpm–200 Nm machine for a direct-drive elevator system. The main technical specifications and characteristics of the commercial PMSM currently in use in the application are shown in Tables 3–5.

The electrical requirements are shown in Table 3, where three different load conditions are presented. The nominal and overload conditions are taken from the working cycle of the machine, which is defined by a particular intermittent periodic duty cycle with electric braking (S5 service). Additionally, a third load condition is defined, which corresponds to 81% of the nominal torque. This load condition corresponds to the maximum torque for which the temperature in continuous operation (S1 service) does not exceed the thermal restrictions.

### TABLE 3 Electrical specifications of the baseline PMSM

| Parameter         | S1 service | S5 nominal | S5 overload |
|-------------------|------------|------------|-------------|
| Power (kW)        | 2.7        | 3.3        | 5.7         |
| Speed (rpm)       | 160        | 160        | 160         |
| Torque (Nm)       | 162        | 200        | 340         |
| Maximum voltage (V)| 400        | 400        | 400         |
| Maximum current (A)| 20         | 20         | 20          |

### TABLE 4 Geometric characteristics of the baseline PMSM

| Parameter          | Value |
|--------------------|-------|
| Stack length (mm)  | 125   |
| Stator outer diameter (mm) | 300   |
| Air-gap (mm)       | 1     |

The main geometric and thermal characteristics of the PMSM are shown in Tables 4 and 5, respectively.

4 | SynRM AND PMA-SynRM DESIGN CRITERIA

In this section, the main criteria for designing SynRMs and PMa-SynRMs for low-speed high-torque applications are presented.

As already shown in the bibliography, one of the key parameters to obtain good performance characteristics of SynRMs and ferrite PMa-SynRMs is the saliency ratio, $\xi$ [6,17,18]. The higher this ratio, the better the intrinsic power factor, and, thus, the better the performance of the machine in terms of current consumption and efficiency.

Furthermore, in gearless elevation applications, the optimisation of the torque ripple is of the utmost importance and its value is not directly related to the saliency ratio.

Based on the above, the following criteria are derived.

1. First of all, it is well known that low pole numbers are recommended to obtain a high saliency ratio [6,8,17–23].
2. Regarding the winding type and the stator slot number, the following conclusions have been drawn by the authors in Ref. [11]:
   - Integer slot distributed winding (ISDW) machines present a high saliency ratio, especially when one stator slot per pole and phase is used ($q_s = 1$). However, the torque ripple in these cases is considerable. Lower torque ripple values are obtained when $q_s > 1$.
   - Fractional slot distributed winding (FSDW) machines exhibit a satisfying saliency ratio and excellent torque ripple values.
   - Fractional slot concentrated winding (FSCW) machines, in most cases, lead to moderate saliency ratios and very poor torque ripple figures. Among FSCWs, the ones with $q_s = 0.5$ and double layer winding show good saliency ratios, but large torque oscillations.
3. Finally, the literature has demonstrated that the rotor geometry has a profound effect on the performance of reluctance machines. The choice of the rotor barrier shapes is a key aspect in the design and it has been deeply studied in the literature [2,14,24–26]. Due to the usually complex rotor geometries, it is very difficult to define some global design criteria. Thus, many authors choose to use automatic optimisation methods to define the rotor geometry [12,13,16,24,25,27–30].

Additionally, some other design decisions can be applied for this particular application:

- Being a low speed application, smaller air-gap length values are mechanically feasible. Furthermore, in the case of SynRMs, the absence of permanent magnets eases the insertion of the rotor into the stator during the manufacturing process. Therefore, thinner air-gaps than in PMSMs can be used in SynRMs.
- When ferrite magnets or no magnets are used, the maximum rotor temperature allowed in reluctance designs is higher than for PMSMs. Thus, the stator working temperature can be higher without risk of damaging the magnets. If a higher insulation class is used in the stator, a higher torque density may be obtained at the expense of increasing the insulation material cost.
- Small rotor diameter and low speed machines present low mechanical stresses in the barrier bridges. This allows to use thinner barrier bridges, leading to higher saliency ratios.
- Since the supply frequency in this application is very low, copper losses are dominant with regard to iron losses. If a higher permeability and thicker steel lamination was used, iron losses could be slightly higher, but the rest of performance characteristics would increase and the material cost would be reduced.

5 | SynRM VERSUS PMSM

Based on the design criteria shown in Section 4, a SynRM has been designed for the same electric specifications of the PMSM presented in Section 3.

A two pole pair integral slot distributed winding (ISDW) machine has been chosen, with 48 slots and one slot short pitching. Additionally, some other changes have been applied following the design aspects discussed in the previous section, such as reducing the air-gap thickness (0.8 mm instead of 1 mm) and using a higher insulation class (H class insulation instead of F class insulation).

Concerning the rotor, a geometry with elliptic barriers has been selected, which has proved to be a good solution [2,14,24,25,29]. The rotor geometry has been defined employing the MODE automatic optimisation method. More than 3000 design candidates have been evaluated within the optimisation process. Among them, the one with the best mean torque and torque ripple combination has been chosen, resulting in the geometry shown in the Figure 4.

As a first design, a SynRM with the same stack length as the PMSM (i.e. 125 mm) has been proposed, but the thermal calculation has shown that the machine is not capable of producing the same torque as the original PMSM without exceeding the maximum allowable temperature in S1 service (i.e. 180°C in the winding). In this regard, the thermal evaluation shows that a 31 mm longer stack is needed to meet the thermal restrictions.

Therefore, a SynRM with a 156 mm stack has been finally designed and calculated. The number of winding turns has also been adjusted to meet the voltage specification. The main characteristics of the designed machine are shown in Table 6.

### Table 5  Thermal constraints of the baseline PMSM

| Parameter                                      | Value   |
|------------------------------------------------|---------|
| Cooling system                                | Natural convection |
| Maximum winding temperature °C (F class insulation) | 155     |
| Maximum magnet temperature °C (N40H class NdFeB magnets) | 120     |

### Table 6  Prototype SynRM characteristics

| Parameter               | SynRM   |
|-------------------------|---------|
| Number of pole pairs    | 2       |
| Number of stator slots  | 48      |
| Stack length (mm)       | 156     |
| Stator outer diameter (mm) | 300   |
| Rotor inner diameter (mm) | 85      |
| Air-gap length (mm)     | 0.8     |
| Winding turns           | 37      |

![Figure 4 Designed synchronous reluctance machines geometry](image-url)
5.1 Results comparison

The results obtained during S1 service for the designed SynRMs and the original PMSM by applying the maximum torque per ampere (MTPA) control strategy are shown in Table 7.

The SynRM needs a 31 mm longer stack to obtain the same torque as the baseline machine in S1 service and, at the same time, it is required to increase the phase current, due to the lower power factor.

The torque ripple, efficiency and power factor values obtained for the SynRM are considerably worse than for the PMSM. Nevertheless, it is noticeable that the obtained figures are excellent for a SynRM.

The obtained results working at nominal and overload condition are shown in Tables 8 and 9, respectively.

The results show the same trend as for the S1 service results: higher current values are required to obtain the specified torque and significantly poorer torque ripple, efficiency and power factor values are obtained.

Finally, a cost comparison of the original PMSM and the designed SynRM is shown in Table 10. Material and manufacturing costs to adequately compare the different designs have been provided by Lancor 2000, S.Coop.

In observing the previous table, it can be seen that the magnet cost, which is the greatest material cost for the baseline PMSM, is completely eliminated. The magnetic steel and copper cost is higher for the SynRM and the increase of the insulation cost is almost negligible if compared with the total cost of the machine. This leads to a significant cost reduction of the 32% for the active parts.

Apart from the active parts’ cost, the cost of the rest of the components and the manufacturing cost are considered. It can

| Table 7 SynRM–PMSM results comparison, S1 service |
| Parameter | PMSM | SynRM |
| Electromagnetic torque (Nm) | 162 | 162 |
| Torque ripple (%) | 0.4 | 2.8 |
| RMS phase current (A) | 6.5 | 7.9 |
| RMS line voltage (V) | 330 | 332 |
| Apparent power (kVA) | 3.7 | 4.5 |
| Input power (kW) | 3.4 | 3.8 |
| Output power (kW) | 2.7 | 2.7 |
| Power factor | 0.9 | 0.84 |
| Efficiency (%) | 81 | 71 |
| Max. winding temperature (°C) | 131 | 179 |
| Magnet temperature (°C) | 117 | – |

| Table 8 SynRM–PMSM results comparison, S5 nominal |
| Parameter | PMSM | SynRM |
| Electromagnetic torque (Nm) | 200 | 200 |
| Torque ripple (%) | 0.4 | 2.4 |
| RMS phase current (A) | 7.3 | 9.6 |
| RMS line voltage (V) | 330 | 324 |
| Apparent power (kVA) | 4.2 | 5.4 |
| Input power (kW) | 4 | 4.4 |
| Output power (kW) | 3.4 | 3.4 |
| Power factor | 0.94 | 0.81 |
| Efficiency (%) | 85 | 77 |

| Table 9 SynRM–PMSM results comparison, S5 overload |
| Parameter | PMSM | SynRM |
| Electromagnetic torque (Nm) | 340 | 340 |
| Torque ripple (%) | 0.4 | 1.8 |
| RMS phase current (A) | 11.5 | 16.6 |
| RMS line voltage (V) | 398 | 381 |
| Apparent power (kVA) | 7.9 | 11 |
| Input power (kW) | 7.2 | 8.5 |
| Output power (kW) | 5.7 | 5.7 |
| Power factor | 0.91 | 0.78 |
| Efficiency (%) | 79 | 67 |

| Table 10 SynRM–PMSM cost comparison |
| Parameter | PMSM | SynRM |
| Magnet type | N40H | – |
| Magnet weight (kg) | 2.4 | – |
| Price/kg (€/kg) | 60 | – |
| Magnet cost (€) | 146 | 0 |
| Magnetic steel | M800-65A | M800-65A |
| Steel weight (kg) | 88 | 110 |
| Price/kg (€/kg) | 1 | 1 |
| Steel cost (€) | 88 | 110 |
| Copper weight (kg) | 12 | 15 |
| Price/kg (€/kg) | 7 | 7 |
| Copper cost (€) | 82 | 102 |
| Insulation class | F | H |
| Insulation weight (kg) | 0.2 | 0.2 |
| Price/kg (€/kg) | 18 | 23 |
| Insulation cost (€) | 3 | 5 |
| Subtotal Active parts (€) | 318 | 216 |
| Other (€) | 770 | 778 |
| Manufacturing (€) | 425 | 375 |
| Total (€) | 1513 | 1369 |
be seen that the manufacturing cost is reduced because no process of embedding the magnets is required and the cost of other components (bearings, shaft, pulley, brake etc.) keeps almost invariable. If the total cost of the machine is considered, the total cost of the machine is reduced just by a 10% due to the large proportionate cost of the non-active parts.

It should be taken into account that these costs very much depend on the manufacturing volume and the manufacturer’s capabilities, and that some of the included components (i.e. pulley and brake) do not strictly belong to the electrical machine. Therefore, in the authors’ opinion, a fairer cost comparison between different machines is done when only the active parts’ and the manufacturing cost are considered.

It can be concluded that a SynRM with a 25% longer stack and a higher insulation class can be a good solution to replace the baseline PMSM. On the one hand, the SynRM completely eliminates the rare earth permanent magnet dependency and, hence, a 10% of the cost reduction is obtained, as well as many other advantages, such as the reduction of environmental cost. Even though the mass of the PMSM is lower and the efficiency is significantly higher, contributing to energy sustainability, the production of rare-earth permanent magnets is energy/material intensive and heavily polluting [31]. Therefore, the SynRM is expected to reduce the overall environmental footprint. On the other hand, lower performance characteristics are obtained and the overall machine’s size and weight are increased by 5%.

6 | PMA-SynRM VERSUS PMSM

In this section, a ferrite PMA-SynRM candidate designed following the same principles as in the previous section is presented.

In the same way as the SynRM design, a two pole pair ISDW machine has been chosen with the same 48-slot 11/12 pitch winding.

Nonetheless, the rotor geometry is completely different. A rotor geometry with prismatic barriers has been chosen, in which ceramic ferrite magnets are introduced. The electromagnetic characteristics of the chosen magnet type are shown in the Table 11.

The geometry of the rotor barriers and the magnets has likewise been defined employing the MODE automatic optimisation method, resulting in the geometry shown in Figure 5.

On the one hand, it has been decided to use a higher insulation class (H class insulation instead of an F class insulation). On the other hand, the air-gap length has been kept to 1 mm, as in the case of the baseline PMSM.

Similar to the SynRM case, a machine 125 mm long has been initially designed and calculated. Once more, the thermal calculation has shown that the machine is not capable of providing the specified torque in S1 service without exceeding the maximum allowable temperature (i.e. 180°C in the winding). To solve this issue, a 12 mm longer stack is needed in order to give the same torque as the original PMSM in S1 service.

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**TABLE 11** Y40 ferrite magnet characteristics

| Parameter                      | Value |
|--------------------------------|-------|
| Remanence, \( B_r \) (T)       | 0.45  |
| Coercivity, \( H_{cr} \) (kA/m) | 342   |
| Intrinsic coercivity, \( H_{ci} \) (kA/m) | 350   |
| Maximum temperature (°C)       | 250   |

**FIGURE 5** Designed permanent Magnet magnet-assisted synchronous reluctance machines geometry

**TABLE 12** Prototype PMa-SynRM characteristics

| Parameter                   | PMa-SynRM |
|-----------------------------|-----------|
| Number of pole pairs        | 2         |
| Number of stator slots      | 48        |
| Stack length (mm)           | 137       |
| Stator outer diameter (mm)  | 300       |
| Rotor inner diameter (mm)   | 85        |
| Air-gap length (mm)         | 1         |
| Winding turns               | 37        |

The main characteristics of the designed machine are shown in Table 12.

6.1 | Results comparison

Table 13 presents the results obtained for the designed PMa-SynRM when controlled under a MTPA control strategy and working under a S1 service. These results are compared with these for the PMSM under the same conditions.

The results obtained when under nominal and overload condition are shown in Tables 14 and 15, respectively.

The simulation results show that the PMa-SynRM needs slightly higher currents than the PMSM for the same torque requirements, the obtained efficiency values are lower, but similar power factor values are obtained. The obtained torque ripple values are higher, especially at overload conditions.

A cost comparison of the original PMSM and the designed PMa-SynRM is presented in Table 16.

It is noticeable that the magnet cost is significantly reduced for the PMa-SynRM. The magnetic steel and copper cost is
slightly higher for the PMa-SynRM and the increase of the insulation cost is almost negligible, leading to a 37% reduction of the active parts' cost.

The manufacturing cost and the cost of the rest of the components keep almost invariable. In conclusion, the PMa-SynRM design is significantly cheaper than the PMSM. If the total cost of the machine is considered, an 8% cost reduction is obtained with the PMa-SynRM.

It can be concluded that a PMa-SynRM with a 10% longer stack and a higher insulation class can be a good solution to replace a PMSM. On the one hand, the rare earth dependency is eliminated (ferrite magnets are used), obtaining an 8% lower cost of the machine. On the other hand, slightly lower performance characteristics are obtained in terms of efficiency and power consumption and the overall machine's size and weight are increased by 2%.

### TABLE 13 PMa-SynRM–PMSM results comparison, S1 service

| Parameter                          | PMSM  | PMa-SynRM |
|-----------------------------------|-------|-----------|
| Electromagnetic torque (Nm)       | 162   | 162       |
| Torque ripple (%)                 | 0.4   | 2.4       |
| RMS phase current (A)             | 6.5   | 6.9       |
| RMS line voltage (V)              | 330   | 344       |
| Apparent power (kVA)              | 3.7   | 4.1       |
| Input power (kW)                  | 3.4   | 3.8       |
| Output power (kW)                 | 2.7   | 2.7       |
| Power factor                      | 0.9   | 0.92      |
| Efficiency (%)                    | 81    | 72        |
| Max. winding temperature (°C)     | 131   | 159       |
| Magnet temperature (°C)           | 117   | 178       |

### TABLE 14 PMa-SynRM–PMSM results comparison, S5 nominal

| Parameter                          | PMSM  | PMa-SynRM |
|-----------------------------------|-------|-----------|
| Electromagnetic torque (Nm)       | 200   | 200       |
| Torque ripple (%)                 | 0.4   | 2.3       |
| RMS phase current (A)             | 7.3   | 8         |
| RMS line voltage (V)              | 330   | 331       |
| Apparent power (kVA)              | 4.2   | 4.6       |
| Input power (kW)                  | 4     | 4.2       |
| Output power (kW)                 | 3.4   | 3.4       |
| Power factor                      | 0.94  | 0.93      |
| Efficiency (%)                    | 85    | 79        |

### TABLE 15 PMa-SynRM–PMSM results comparison, S5 overload

| Parameter                          | PMSM  | PMa-SynRM |
|-----------------------------------|-------|-----------|
| Electromagnetic torque (Nm)       | 340   | 340       |
| Torque ripple (%)                 | 0.4   | 3.5       |
| RMS phase current (A)             | 11.5  | 13.2      |
| RMS line voltage (V)              | 398   | 392       |
| Apparent power (kVA)              | 7.9   | 8.9       |
| Input power (kW)                  | 7.2   | 8         |
| Output power (kW)                 | 5.7   | 5.7       |
| Power factor                      | 0.91  | 0.9       |
| Efficiency (%)                    | 79    | 71        |

### TABLE 16 PMa-SynRM–PMSM cost comparison

| Parameter                          | PMSM       | PMa-SynRM |
|-----------------------------------|------------|-----------|
| Magnet type                       | N40H       | Y40       |
| Magnet weight (kg)                | 2.4        | 0.9       |
| Price/kg (€/kg)                   | 60         | 10        |
| Magnet cost (€)                   | 146        | 9         |
| Magnetic steel                    | M800-65A   | M800-65A  |
| Steel weight (kg)                 | 88         | 96        |
| Price/kg (€/kg)                   | 1          | 1         |
| Steel cost (€)                    | 88         | 96        |
| Copper weight (kg)                | 12         | 13        |
| Price/kg (€/kg)                   | 7          | 7         |
| Copper cost (€)                   | 82         | 89        |
| Insulation class                  | F          | H         |
| Ins. weight (kg)                  | 0.2        | 0.2       |
| Price/kg (€/kg)                   | 18         | 23        |
| Ins. cost (€)                     | 3          | 4         |
| Subtotal active parts (€)         | 318        | 199       |
| Other (€)                         | 770        | 775       |
| Manufacturing (€)                 | 425        | 425       |
| Total (€)                         | 1513       | 1399      |

**FIGURE 6** PMSM–PMa-SynRM–SynRM performance comparison. PMa-SynRM, permanent Magnet magnet-assisted synchronous reluctance machines; PMSM, permanent magnet synchronous machines; SynRM, synchronous reluctance machines
Additionally, the PMa-SynRM is presented as a better alternative in terms of environmental and human health impact [32].

Finally, a radar graph with a qualitative comparison of some of the main designed machines’ characteristics is presented in Figure 6.

7 | INVERTER CONSIDERATIONS

A no minor issue is to verify that a replacement of a PMSM by a SynRM or a PMa-SynRM does not imply a change or oversizing of the required inverter for the application.

The main parameter used for the selection of the proper inverter is the current capacity at a given switching frequency. It has been analyzed whether the increase of the required phase current could imply that a higher power inverter shall be employed. The catalogues of two major manufacturers specialised in lift application inverters have been consulted and it has been found that the inverter model which best fits the PMSM requirements is also the best choice for the SynRM and PMa-SynRM [33,34], as can be observed in Table 17.

8 | CONCLUSIONS

The feasibility of replacing a PMSM by a SynRM and a PMa-SynRM for low-speed high-torque applications has been studied in this work, with special focus on the cost of the machine.

The main criteria for designing reluctance machines consist on choosing low pole numbers and integer slot distributed winding layouts. Additionally, in order to obtain low torque ripple and high saliency values, automatic optimisation methods have been used to define the rotor geometry. In order to compare to be fair, a higher insulation class has been used and a thinner air-gap has been considered for SynRM design.

The performances of the designed machines have been compared with that of a commercial PMSM for a lifting application. It is found that, for the evaluated machines, the needed active parts’ volume for the same torque requirement and a limited maximum temperature are around 25% larger for the SynRM and 10% larger for the PMa-SynRM. Moreover, the SynRM presents a significantly worse performance in terms of torque ripple, efficiency and power factor, while the PMa-SynRM presents a similar power factor and a slightly worse efficiency and torque ripple compared with the PMSM.

Future work regarding the torque ripple issue may be conducted. Some additional design or control techniques should be applied, such as skewing the rotor or the stator, for the designed reluctance machines to obtain results comparable to reference PMSMs.

Finally, a cost comparison between the baseline PMSM and the designed machines has been carried out. It is found that, for the evaluated machines, a significant cost reduction is obtained as follows: up to 10% for the SynRM and 8% for the PMa-SynRM when considering the total actuator cost. If just the cost of the active parts is evaluated, the improvements are much greater—up to 32% for the SynRM and 37% for the PMa-SynRM.

In the case of the ferrite PMa-SynRM, it is expected that a properly designed machine could substitute the current PMSM for the application at hand, obtaining an acceptable performance with a slightly greater machine size and weight, but a significant cost reduction.

In the case of the SynRM, most of the metric results are worse than for the PMSM. Nevertheless, the SynRM completely eliminates the rare-earth permanent magnet dependency, deriving from some other advantages, such as no demagnetisation risk, improved fault-tolerance and reduced machine cost.

ACKNOWLEDGEMENTS

This research has been supported by Lancor 2000, S.Coop. The authors would like to thank Lancor 2000, S.Coop. for providing information on material and manufacturing costs and greatly assisting this research work.

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