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Synchronous Reluctance Machines: A Comprehensive Review and Technology Comparison

This article reviews the promising synchronous reluctance machine technology, covering its background and evolution, as well as the latest developments in the field.

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ABSTRACT | In the last decade, the trend toward higher efficiency and higher torque density electrical machines (EMs) without permanent magnets (PMs) for the industrial sector has rapidly increased. This work discusses the latest research and industrial advancements in synchronous reluctance machines (SynRMs), being the emergent motor topology gaining wide acceptance by many industries. This article presents an extensive literature review covering the background and evolvement of SynRM, including the most recent developments. Nowadays, SynRM has found its niche in the EM market, and the reasons for that are highlighted in this work together with its advantages and disadvantages. The key journal publications in SynRM topics are discussed presenting the biggest challenges and the latest advancements with particular regards to the design methodology. This article aims to provide a thorough overview to the research community and industry about SynRM. There is a clear potential for SynRM to take over a significant portion of the EM market in the near future to meet efficiency standards in industrial applications without the use of rare-Earth PM technology.

KEYWORDS | Design methods; high efficiency; industrial drives; review; synchronous reluctance machines (SynRMs).

Manuscript received April 18, 2021; revised November 5, 2021; accepted January 18, 2022. Date of publication February 11, 2022; date of current version March 9, 2022. This work was supported by the University of Nottingham Propulsion Futures Beacon. *(Corresponding author: Mukhammed Murataliyev.)*
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Digital Object Identifier 10.1109/JPROC.2022.3145662

I. INTRODUCTION

In recent years, there is a growing interest in high-efficiency electric motors without or with reduced content of permanent magnets (PMs). Synchronous reluctance machine (SynRM) is one of the most promising candidates that can meet these requirements along with the high efficiency and low cost [1], [2]. The root of all its benefits and drawbacks is related to its rotor structure. The latter is made of a suitably cut stack of laminations without using any excitation coils as in wound rotor machines, short-circuited conductors as in squirrel cage induction machines (IMs) (SCIMs), or PMs in PM machines [3]. This leads to a cost-effective structure that is using the reluctance principle to generate torque.

The SynRM topology was first introduced in the 1920s [4]; however, it was not applicable to industrial applications as other technologies, such as SCIMs, as this can be directly fed from a three-phase supply [5]. SCIMs are still considered the industry "work horse" as it dominates the electrical machine (EM) market in applications such as industrial fans, pumps, and mill-type loads. Indeed, it is the cheapest and the most reliable machine topology based on mature manufacturing processes. In the 1960s,

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after a few decades of research, PMs started to be used for applications requiring high performance.

The rare-Earth PMs started to be commercialized for electrical motors in the early 1980s, introducing a new revolution for the EM sector, due to their high energy density, with respect to previous hard magnetic materials. Various types of applications such as high-performance industrial motors for spindles and compressors, electric vehicles (EVs), wind turbines, and actuators started to adopt PM synchronous machines [6]–[8]. Neodymium–iron–boron (NdFeB) PMs are the most common type of magnets for high-performance applications due to their superior magnetic properties. In comparison, the remanent flux density B_r and coercivity H_c values of NdFeB are higher than any other type of magnets, such as samarium–cobalt (Sm2Co17), which was the major breakthrough in the 1970s [9], and it is still extensively used when high operating temperatures are required.

The main downfall of NdFeB magnets is their cost; moreover, their future availability and embedded carbon emission in their manufacturing processes are also concerning issues. The prices of the PM saw a huge spike in mid-2011, as it increased by a factor of 25 compared to the beginning of 2010 [10], [11]. After hitting its peak, the price dropped rapidly and settled at its prebubble price [12] such price instability had a huge financial effect on PM machine manufacturers. Hence, in the following years, the research on EMs with low usage of rare-Earth-based PMs was intensified [13], [14].

Along with this cost and supply chain concerns, industrial applications have to comply with various standards and regulations, all tending to increase the minimum energy efficiency [3], [15], [16]. This was driven by national and international policies aimed at improving the way energy is produced and consumed, and so minimizing the human footprint and the related greenhouse gas emissions [17], [18].

Currently, world-leading manufacturers, and research and development institutions are constantly investigating the possibility of increasing efficiency using cost-effective solutions. SynRM is a promising technology with features that are well aligned with the above industrial needs: high efficiency and no magnets [10], [12]. Key EM manufacturers, such as ABB, KSB, and Siemens, have already started the serial production of the high-efficiency SynRM [19], [20]. In addition to this, there is a great potential for SynRM in automotive applications as these also require extended field-weakening (FW) capabilities, which can be achieved using low-energy-density PM.

Despite its advantages, there are still a number of issues that are subject to research. From the machine design perspective, the main challenges come from the complex anisotropic structure of the rotor requiring a nonstandard design procedure. The torque ripple, the power factor (PF), and other secondary effects, such as rotor iron losses, vibration, and noise, are the main issues that need to be carefully considered during the design of a SynRM [21], [22].

Fig. 1. ***Number of publications on SynRM topic over the past decade [1].***

According to statistics that were acquired via Google Scholar, from 2009 to late 2020, IEEE, Institution of Engineering and Technology (IET), and Elsevier have published 1789 scientific papers on SynRM; meanwhile, PM motor technologies had over 12 000 manuscripts. Fig. 1 presents the number of publications on the SynRM topic over the past decade. As can be observed, the scientific interest toward SynRM has been constantly growing due to current trends toward rare-Earth element (REE) free technologies and more energy-efficient EMs.

This article covers the main reasons why SynRM is gaining the industry's attention and the recent developments of this topology.

Section II is dedicated to efficiency roadmaps and aims to cover recent and future government regulations for higher efficiency drives. Section III discusses the main economical and supply chain problems of the REE PMs. Basic operational principles of the SynRM in the context of other synchronous EM topologies are discussed in Section IV. In Section V, the state of the art is reported. It discusses the main design challenges and the drawbacks of the SynRM and design methods to address them. Modern design ideas and innovative techniques introduced by the research community with the aim of significantly reducing the effort required to design SynRM are all discussed in detail. Section VI is dedicated to a discussion of SynRM as a potential modern industrial EM. A detailed comparison of the SynRM with other widely spread industrial topologies, such as SCIM and PM machines, is reported. Different SynRM application examples are discussed including an example of a line-start SynRM. A detailed qualitative cost comparison of SynRM with SCIM is presented. Finally, in Section VII, this article provides examples of industrial SynRM that is currently available on the market to prove the wide acceptance of SynRM by the industry.

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Fig. 2. ***EM Efficiency movement timeline, standard 15-kW motor example [39].***

II. NEW EM EFFICIENCY ROADMAPS

As reported in [23] and [24], EMs consume approximately 40% of the total worldwide generated electrical energy, whereas, in the EU, EMs take almost 70% of the total consumed electrical energy. Therefore, improvements in the EM energy efficiency could lead to a significant reduction in power consumption and related carbon emission. The main EU energy and climate goal of 2020 is to achieve the reduction in the greenhouse gas emissions by 20% compared to the 1990 levels [25], [26], by raising the share of the power generation from renewable resources. New regulations according to the 2030 Framework on Climate and Energy were set in 2014 by the European Commission on January 22 and the European Council on October 24. The next milestone was set for a mandatory 40% reduction in greenhouse gas emissions from the 1990 levels, and 27% of the total generated power should come from renewable sources with a target of 27% in terms of energy savings to be achieved.

According to Brunner *et al.* [27], 56% of the motors worldwide exceed their life expectancy. 68% of the utilized motors are oversized having a load that is less by 60% or sometimes 80% of their rated capability. The older machines (normally used to drive fans, pumps, compressors, and so on) are inefficient and usually fall under IE0/IE1 Standards. Moreover, they are less reliable and less performing and require constant maintenance and repair. One of the biggest worldwide industrial problems is the lack of a machine renewal culture [27].

It was highlighted in [28] that the acceptance of the higher efficiency standards for EMs is affected by the existence of the common standards of the motor performance tests, efficiency classification, and labeling. The IE4 Standard was introduced in the first edition of the IEC 60034-30, whereas the Gold Standard Efficiency IE5 was introduced in the second edition.

The three-phase SCIM takes a major portion of the EM market [10], [12]. Currently, major manufacturers already have the capability to produce the SCIMs that meet the IE4 class by using standard frames with aluminum rotor cages [29], [30]. The line-start PM (LSPM) machine is another IE4 class motor; usually, it has the interior rare-Earth PMs (NdFeB) and auxiliary cage for starting.

Fig. 2 shows the motor efficiency class adoption timeline in different countries (15-kW drive example). Fig. 2 was retrieved from [31]; however, it was modified by adding SynRM efficiency capability based on [19] and [32]. The standards highlighted in Fig. 2 are applicable for EMs within a power range between 120 W and 1000 kW with voltages up to 6 kV, and the number of poles of considered machines is two to eight, whereas the thermal operating conditions are between −20 °C up to 60 °C at the 4000-m altitude [33]. Based on the efficiency trends and the capability of SCIMs and PM machine topologies, it can be stated that SynRM can surely have a significant role within the IE4 Premium Efficiency Band.

A. Efficiency Standard Timeline

The strong push toward high efficiency is dictated by the recent EU environmental policies. These are reported in [28], [34], and [35]. The Eco-Design directive is divided into several policy options (POs), listed as follows:

1) PO-1 was accepted on January 1, 2018, and includes the following.
   a) PO-1A implies that targets all single-phase motors rated above 0.12 kW imposing at least the IE2 Standard.
   b) PO-1B implies that three-phase motors with a rated power of greater than 120 W and less than 750 W should meet the IE2 Standard or greater.
   c) PO-1C involves that all three-phase low-voltage (LV) and medium-voltage (MV) motors rated above

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375 kW and below 1000 kW should meet IE3 Standard or greater.

2) PO-2 should be accepted by January 1, 2022, and implies that all the variable speed drives (VSDs) rated above 750 W should meet IE3 Standard.
3) PO-3 was accepted on January 1, 2018, and included the explosion-proof, brake motors, and other Ex-eb[1] motors.
4) PO-4 was accepted on January 1, 2018, and included mandatory requirements for motors and VSD (discussed later).
5) PO-5 was accepted on January 1, 2018, and imposed that all VSDs meet the IE1 performance at minimum energy performance standards (MEPSs).
6) PO-6 should be accepted by January 1, 2022, and includes the following:
   a) PO-6A where MEPS should be raised for SCIMs greater than 750 W and less than 375 kW from IE3 to IE4;
   b) PO-6B where MEPS of larger SCIMs (between 375 kW and 1 MW) should go from IE3 to IE4.

PO4 states that all machine product information requirements and comprehensive detailed technical information should be included on the rating plate for all motors that are rated 120 W–1 MW. The PO5 was introduced to eliminate the usage of the VSD motors that are below the IE1 Standard. PO-6 mainly focuses on the transition to IE4 that should be available at competitive prices compared to IE3 machines.

B. Recent Efficiency Regulations

A very recent efficiency requirement (PO-6A) that took effect on July 1, 2021 states that all motors with a rated output power of greater than 750 W and less than 1000 kW with two, four, six, or eight poles that are not Ex-eb-increased safety motors should meet at least IE3 efficiency. Motors that have the output power of greater than 120 W and less than 750 W with two, four, six, and eight poles that are not Ex-eb should meet IE2 efficiency, whereas all VSDs with the rated output power of greater than 120 W and less than 1000 kW should match IE2 Efficiency Standard.

By July 2023, all Ex-eb motors with rated power in the range between 120 W and 1000 kW with two to eight poles must meet the IE2 requirement. Similarly, single-phase motors with a rated output power of equal or greater than 120 W must match IE2, whereas IE4 efficiency requirement will be compulsory for three-phase non-Ex-eb motors with a rated output power of greater than 75 up to 200 kW with two to six poles.

The overall summary of the recent MEPS updates for motors and drives is depicted in Fig. 3. It can be concluded that the IE1 Standard drives have fallen off the efficiency acceptance list and now are not considered as a viable option according to regulations. The IE2 Standard drives will follow the same fate in the nearest future, whereas IE3 and IE4 will be more common for industrial drives for rated power ranges between 120 W and 1000 kW. In this context, SynRM matches well the future drives' requirements and soon will be widely adopted by most manufacturers.

[1]"Ex-eb"-increased safety motors are certified for installation in hazardous areas.

Fig. 3. ***Efficiency regulations 2021–2023.***

III. PROBLEM WITH PERMANENT MAGNET MATERIALS

PMs are an essential component of modern synchronous motors and generators. Key properties of PMs are coercivity and remanent flux density. These are strongly dependent on the microstructure of the material itself. One of the most widely used PMs for traction motors and power generators contains Nd and Dysprosium (Dy). Dy is used to sustain the NdFeB PMs coercivity at higher temperatures [36]. Both Dy and Nd are considered as REEs and listed as critical materials by the U.S. Department of Energy and other international institutes due to the high risk in supply [37]. Other alternatives are the nonrare-Earth (non-RE) PMs that, although have lower magnetic performance, are still attractive for many applications where cost saving is a priority.

The request for NdFeB PMs has been significantly increasing due to the demanding needs of modern drives applications: higher energy efficiency, performance, and power density. Fig. 4 presents the average price of Dy_2O_3

Fig. 4. ***REE oxides' price trends. The data were retrieved from the USGS Mineral Commodities Summaries [1], [38].***

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Table 1 Comparison of PM Prices and Their Properties [46]

	$(BH)_{max}$ (MGOe)		H_{ci} (kOe)		Br (kG)		Price ($/kg)	
	2016	2022	2016	2022	2016	2022	2016	2022
NdFeB (NH42SH)	40-42	42	20	20	13-13.3	13	60$	120$
Sm-Co (SC-3215)	31-32	34	15	15	11.2-11.8	12	128$	210$
AlNiCo-9	9	11	1.4	2	10.5	10.5	71$	80$
Ferrite (Sr-8B)	3.8	3.8	3	3	4	4	4$	4$

and Nd_2O_3 according to USGS Mineral Commodities Summaries. The average price of the Dy oxide has spiked from 245 $/kg in 2010 to 1410 $/kg in 2011 and then gradually went down to 185 $/kg in the following five years. The price of the Nd oxide has also raised from 88 $/kg in 2010 to 195 $/kg in 2011 and then went also down to 39 $/kg [38]. The increase in the Nd oxide average price was mainly caused by a huge increase in demand in REE and the monopoly of the critical REE mines in specific areas of the globe. After 2016, there has been an obvious divergence in the price of the two oxides, as shown in Fig. 4. This happened due to the successful reduction of usage of the Dy element. In addition, China and the biggest European countries are currently forcing the EV market to replace the internal combustion engines, which are expected to be phased out in two decades. With the increase in the number of EVs, the Nd price will continue to grow, and this constitutes the main driver for the industrial interest in REE-free PM and EMs.

Based on the market report that was presented in [39], in 2015, the sales of NdFeB, SmCo, ferrite, and alnico are $2927M, $722M, $4344M, and $355M, respectively. According to the PM sales report, ferrite is dominant by occupying nearly half of the market. Ferrite PMs are very popular for motors that do not require high power densities. However, for those applications that are limited in size and weight, i.e., aerospace applications or EVs, REE magnets are the only viable choice. The most pragmatic approach to reduce the usage of REE is developing non-REE magnets that can fill the magnetic performance gap between ferrite and REE magnets [46]. Table 1 presents the prices and properties of the various PMs in 2016 and the predicted values in 2022. The table presents the cost properties ratios $/kg/kG/kOe, where the magnet cost per kg $/kg is divided by the remanent magnetization kG and the coercivity kOe. It is desired to develop non-RE magnets that will have a higher value of cost property ratio ($/kg/kG/kOe).

The strategies to address the REE problem are increasing and diversifying the supply sources and reducing the demand. China, Australia, the United States, and Vietnam have started to open new REE mines including the Dy ones. However, none of the newly opened mines can compete with the existing ones that are rich in REE deposits that are mostly based in China. To reduce the demand in REE, non-RE or less-RE PM technology is being investigated. Significant advancement in reducing Dy content in NdFeB, while still keeping a high level of coercivity, was achieved by the reduction of the grain size of the PM [40]. The development of the EM technologies that do not require the PM fields is one of the key approaches to solve the described problem.

Another major drawback of REE is that sourcing and processing are very carbon-intensive, and recycling is still immature. In [41], an in-depth analysis of REE PMs is given, highlighting their impact on the environment. Indeed, in order to make REE PM more environmentally sustainable, there is a need to push toward recycling solutions.

In summary, it can be concluded that the current trends toward higher efficiency and REE-free technologies make EMs based on the reluctance principle a serious alternative. The rapid industrial acceptance of the SynRM is a matter of time, as the biggest motor manufacturers, and research and development institutions are working toward the described challenges.

IV. OPERATING PRINCIPLES OF SYNCHRONOUS RELUCTANCE MACHINES

In this section, the operating principles of SynRM are compared with other synchronous machine topologies. The reluctance torque, also known as alignment torque, is due to the forces that occur when a magnetic material interacts with a magnetic field. The torque produced in SynRM is caused by unequal magnetic permeability in the transverse and longitudinal axes of the rotor that has no windings or PM excitation. The ac current flowing through the stator windings creates a rotating magnetic field in the air gap of the motor that rotates at the synchronous speed, and the rotor follows the magnetic field without reaching the magnetic field itself; therefore, the machine continuously produces torque.

The reluctance motor described within the synchronous d–q reference frame, the d-axis is considered the path of lower reluctance (high flux-to-MMF ratio), while the q-axis is the path of higher reluctance (since the flux-barriers obstructing the flux). Therefore, the saliency ratio ξ,

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Fig. 5. ***All possible combinations of reluctance and PM torque components [1].***

defined as the ratio between the d- and q-axis inductances, has to be maximized [12].

A. Synchronous Topologies Classification

Synchronous machines can be also classified based on their torque production phenomena: PM torque and reluctance torque. PM torque is the torque that occurs between two interacting magnetic fields, i.e., PM machine having rotor field produced by PMs and stator field generated by stator currents [12], [42].

The fundamental torque equation for cylindrical machines in the d–q frame represents both phenomena

$$T_{dq} = 1.5p\left[\left(L_d - L_q\right) i_d i_q + \lambda_{\mathrm{pm}} i_q\right] \tag{1}$$

where $(L_d - L_q) i_d i_q$ is the reluctance component and $\lambda_{\mathrm{pm}} i_q$ is the PM part. The relative proportion of the PM and reluctance torque components will depend on the amount of PM (or any other rotor field source) and the amount of rotor's magnetic saliency. Hence, there is a huge number of possible combinations that can be applied in (1) [12]. An effective way to visualize the classification of synchronous machines is shown in Fig. 5. Here, the saliency ratio quantifies the capability of the reluctance torque. The saliency ratio is defined as

$$\xi = L_d / L_q. \tag{2}$$

Fig. 5 highlights four main synchronous machine topologies. SPM is a surface-mounted PM machine, which has "no saliency" ($\xi = 1$). This topology contains pure PM torque (1). IPM is an interior PM machine, and it has saliency; however, it mainly relies on the PM torque component. PM-assisted SynRM (PMaSynRM) is designed in such a way that the machine mainly relies on the reluctance torque component, whereas SynRM is a pure reluctance torque machine. All four rotor topologies are presented in Fig. 6.

The common way of representing the d–q-axis for synchronous machines is that the d-axis is always the axis of the higher flux. In fact, in the PM machine, the main flux is given by the PM's [see Fig. 6(a) and (b)], while, in the reluctance machine, it is where permeability is higher [see Fig. 6(c) and (d)] [43]. As can be observed in Fig. 6(a), surface PM rotors exhibit no saliency, and this rotor topology has a uniform iron rotor, whereas the PMs are mounted on top of it. Hence, the magnetic permeability of d- and q-axes is ideally uniform ($L_d = L_q$) when the machine is not highly saturated. In general, the inductances of the surface-mounted PM are quite low since the magnet has very low relative permeability. Hence, the magnets, which are mounted on the rotor iron surface, increase the effective air-gap length. The magnets are exposed directly to the armature field and, hence, are subject to partially irreversible demagnetization [44].

The IPM rotor has the magnets buried in rotor lamination Fig. 6(b), hence introducing saliency, as the rotor iron geometry is nonuniform. The magnetic conductivity of d- and q-axes is not equal, as the magnets that are placed in the q-axis direction have a much lower magnetic permeability compared to the iron ($L_q > L_d$). Multilayers of magnets can be used to further increase the saliency. One of the advantages of the IPM is that the magnets are effectively shielded from the demagnetizing armature field during the flux weakening operation [45]. Since $L_d < L_q$, these machines usually operated in the second quadrant of the (i_d, i_q) plane. As discussed in [45], the q-axis inductance is usually higher compared to an equivalent SPM; therefore, generally, IPMs are more suitable if a wide constant power speed range is desired. Indeed, the constant power in the flux-wakening mode of operation is achievable at lower volt–amps ratings compared to the surface-mounted PM machine [46]–[48].

The PMaSynRM rotor, as shown in Fig. 6(c), usually (but not always), has weaker magnets or lower magnet volume and, hence, indicates less PM torque compared to IPM. However, it has much higher saliency due to the higher number of flux barriers. The interior flux barriers are placed in the q-axis direction ($L_d > L_q$). In order to increase the reluctance torque component, the rotor anisotropy is maximized by introducing more than one flux barrier [49]. This topology shares similar features with IPM in terms of constant power achieved during flux-weakening operation. This machine topology mainly relies on the reluctance torque component, and it exhibits several drawbacks related to the torque ripple, low PF, and mechanical constraints related to the flux barriers retention [21], [50].

Pure SynRM rotor has no magnets and, hence, exhibits no PM torque. This topology has a much higher saliency ratio along the q-axis compared to other topologies

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Fig. 6. ***PM to reluctance machine topologies [1].***

($L_d > L_q$) [51]. Similar to PMaSynRM, SynRMs feature demanding rotor mechanical constrains and higher torque ripple. Due to the presence of the iron ribs that physically hold the whole rotor structure together, the cross-saturation effect occurs [52], [53], as the d and q rotor axes are not completely magnetically isolated due to the presence of a shared flux path area, such as the iron bridges. Hence, an accurate FE-evaluation of the machine's electromagnetic performance is required.

B. Torque Performance Comparison

To better visualize the torque operation of different synchronous machine topologies, the constant torque curves are presented in Fig. 7 in p.u. values.

As can be observed in Fig. 7(a), the SPM torque performance depends only on i_q; however, at higher currents, the maximum torque per ampere (MTPA) control strategy requires a negative i_d. This happens because the d-axis inductance saturates at lower currents with respect to the q-axis one.

Since IPM has both reluctance and PM torque components [see Fig. 7(b)], it requires both i_d and i_q currents to follow the MTPA. Since the d-axis inductance is smaller than the q-axis inductance, higher torque is achieved with the negative i_d. The torque curves are dependent on both i_d and i_q; therefore, detailed electromagnetic analysis or experimental identification is required to derive the MTPA lookup table [54].

The PMaSynRM topology [see Fig. 7(c)] operates in the first quadrant as the d-axis inductance is greater than the q-axis inductance. As can be observed, the PMaSynRM torque curves are somewhat mirroring the IPM torque behavior with respect to the i_q-axis; however, the MTPA is inclined toward the i_q-axis. It is important to note that, for this topology, the rotor q-axis is aligned with the magnet; hence, i_d is required to get PM torque (see Fig. 7).

As can be observed from Fig. 7(d), the SynRM MTPA trajectory is further inclined toward the i_q-axis compared to PMaSynRM, as there is no PM torque component. The SynRM's torque curves are highly dependent on the d-axis inductance saturation levels, whereas it is desired to minimize the q-axis inductance. It can be observed that the SynRM, PMaSynRM, and IPM torque profiles are more current-angle-dependent as the MTPA trajectory changes rapidly. This is caused due to the salient nature of the rotor, meaning that torque is entirely or partially produced by reluctance torque, due to interaction of the stator currents

Fig. 7. ***Constant torque curves with highlighted MTPA trajectory on the (i_d, i_q) plane [1]. (a) SPM. (b) IPM. (c) PMaSynRM. (d) SynRM.***

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Fig. 8. *"Equal pitch" rotor for the two-pole configuration [57].*

with the anisotropic rotor structure. Its operating principle is, thus, highly dependent on the saturation levels of the iron material. Based on these, it can be said that the current phase angle will vary considerably with respect to the current-torque levels of the operating instance, which leads to a relatively complex control strategy. However, in the past decade, it has been demonstrated that both sensored and sensorless implementations are possible due to the knowledge of the machine's electromagnetic model [12], [55].

The above considerations justify the slower adoption of SynRM, which presents some challenges requiring a more complex control strategy compared with PM machines. This can be considered as one of the historical main barriers to the wide industrial acceptance of SynRM since it requires a more expensive drive and control platform needed to implement the more complex control algorithms.

V. STATE OF THE ART

This section discusses the research works that contributed to address the main design challenges of the SynRM.

The rediscovery of the SynRM and its design challenges started in the early 1990s. Important works related to the SynRM geometry and design procedures were addressed by the pioneering works of Vagati [56], Vagati *et al.* [51], [58], and Fratta *et al.* [57]. In particular, in [56], a SynRM drive was compared with the brushless REE PM machine and IM. It concluded that SynRM has great potential in the industrial sector as it can achieve a relatively high torque density at a competitive cost.

A. Key Design Challenges

Historically, the main streams of the research works have been covering the SynRM design challenges: maximizing average torque [4], [59], [60], minimizing torque ripple [21], [61], [62], and improving the PF [61], [63] and the comparison with other topologies [4], [59], [64]–[66].

In [51], the main problems of the SynRM design were outlined highlighting for the first time all the compromise of the reluctance torque production, namely, the maximization of the anisotropy, the magnetizing flux, and the q-axis current. Different rotor and stator structures were investigated. In this work, for the first time, the mechanical problem associated with the ribs was also highlighted. In [57], the SynRM torque ripple was analytically evaluated, and the effect of the barriers' angular position at the air gap on the torque ripple was studied. The concept of the "equal pitch" rotor flux barrier distribution, as shown in Fig. 8, featuring multiple iron segments was first introduced and analyzed. Another work addressing the identification of the optimal rotor geometry for low torque ripple was presented in [58], and it aimed to outline a general design approach.

One of the early rotor design optimization methods of SynRM was presented in [67]. The key objective of the optimization was to improve the PF. It was proven that the PF of 0.8 is a practicable achievable value. In [68], various factors affecting the saliency ratio were investigated. It was shown that the rotor design and, in particular, the number of barriers have the most significant impact. Indeed, maximizing the number of rotor barriers increases the saliency ratio although there is a physical limit to their maximum number.

A higher number of barriers can be achieved by adopting an axially laminated rotor (ALA). The main difference between the conventional transverse laminated rotor (TLA) and ALA is in the manufacturing process. Fig. 9 shows the assembly process of the ALA and TLA topologies. As can be seen, the ALA rotor is assembled by placing the iron rotor pieces axially kept by pole holder bolts, whereas the TLA is conventionally assembled by stacking rotor lamination together. It was proven in [71] that ALA topology can significantly improve performance by an increase in saliency, PF, and torque capability. An example of an ALA SynRM rotor is reported in Fig. 10.

Even though ALA topology seems to have several superior features that come from the significant increase of the barrier numbers, it still has issues liming its commercialization. The problem associated with increased iron losses of this topology is considered a minor drawback; nevertheless, it significantly limits its efficiency advantages. Challenges of manufacturability play a more important role, as the ALA is more difficult to assemble when compared to the conventional TLA structure [12].

In terms of manufacturing for a high-volume production, where the lamination cutting is done by punching techniques, the TLA manufacturing difficulty can be

Fig. 9. *ALA and TLA SynRM topologies [69], [70].*

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Fig. 10. ***Assembled ALA rotor topology [71].***

considered equivalent to IPM machines where the retention of the rotor structure and PMs is done by iron ribs.

B. Complex Geometry

Based on all the above, it can be stated that the main machine design challenge comes from the fact that SynRM has a very complex structure; therefore, many geometrical parameters are involved in machine sizing and optimization. Many works have attempted to address the rotor complexity, as in [51], [59], and [72]–[74].

One of the recent SynRM rotor design methods that are currently widely used was introduced in [75]. The goal of this work was to introduce an easy approach to the design and optimization by a comprehensive parameterization of the rotor geometry, as highlighted in Fig. 11.

Various analytical methods usually based on the lumped magnetic circuit of the machine are used to identify the optimal distribution of air insulation along the q-axis of the rotor [51], [69]. However, time-consuming finite element-based optimization is still a necessary step to address the optimization of the main performance indexes (torque ripple reduction, loss reduction, and so on). The SynRM rotor complexity naturally increases the time and the steps

Fig. 11. ***Rotor geometry and related microscopic and macroscopic parameters [75].***

that are required during the design optimization stage [21], [74], [76], [77].

The computation time varies according to which performance targets are being optimized (torque, torque ripple, iron losses, and so on), and Degano *et al.* [21], Bianchi and Mahmoud [22], Mahmoud *et al.* [78], and Pellegrino *et al.* [79] have investigated the problem of establishing the tradeoff between accuracy and computational burden.

On the other hand, the geometrical complexity of the problem can be further reduced acting on how the rotor geometry is parameterized. In particular, Gamba *et al.* [62] and Pellegrino *et al.* [79] present a comparative study among different SynRM flux barrier parameterizations, analyzing the compromise between geometrical complexity, achieved performance, and computational time. It is a general conclusion that adopting a flux barrier profile described by the Joukowski equation and a flux barrier parameterization described by three parameters (barrier thickness, air-gap angle, and end-barrier parameter) is the best compromise between performance and geometrical complexity [62], [75]. These parameters are also the ones, which most affect the torque performance, and for this reason, they are usually optimized during the FE refinement stage.

C. Accurate Analytical Sizing

A preliminary analytical sizing is usually the first step of any EM design procedure. In this step, the machine general dimensions are determined [80]–[82]. The classical sizing approach of a SynRM relies on the torque relation for common cylindrical machines derived from the magnetic field energy at the EM's air gap whose general expression is

$$T \sim V \cdot B \cdot A \tag{3}$$

where T is the torque, V is the rotor volume, B is the air-gap flux density usually referred to as the magnetic loading, and A is the linear current density referred to as the current loading.

A novel sizing approach that is capable to consider the EM's rotor salient nature was introduced in [83]. The saliency (2) was derived by considering the magnetizing coefficients of both d- and q-axes that quantify the magnetic conductivity of the respective axes [69]. The saliency can be then derived as

$$\xi = \frac{L_d}{L_q} = \frac{L_{dm} + L_l}{L_{qm} + L_l} = \frac{L_m K_{dm} + L_m K_{qm}}{2 L_m K_{qm}} \tag{4}$$

where L_m is the magnetizing inductance, L_l is the leakage inductance, and K_{dm} and K_{qm} are d- and q-axis magnetizing coefficients. The main assumption is that L_{qm} is assumed to be associated with leakage flux. Therefore, $L_l = L_{qm}$.

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In [83], the general dimensioning equation was derived considering the salient nature of the machine using equation

$$D_{\mathrm{ro}} = \sqrt{\frac{T\gamma\,\mu_0 q K_{dm}\sqrt{\xi}}{B_{1d}^2 \pi g \sqrt{1+\left(\frac{1}{2\xi-1}\right)^2}\,\xi}} \tag{5}$$

where D_{ro} is the rotor diameter, q is the number of slots per pole per phase, g is the air-gap length, and μ_0 is the relative permeability of free space, while the aspect ratio γ is defined as

$$\gamma = \frac{L}{D_{\mathrm{ro}}} \tag{6}$$

with L being the stack length.

D. Torque Ripple Optimization

In [75], a novel fast and systematic design procedure for SynRM was introduced. The average torque and torque ripple optimization workflow revolves around finding the best combination of barrier geometries and stator geometrical parameters. Three design parameters are considered, which are the insulation ratios in the q-axis, the barriers' angle distribution, and stator geometrical parameters. These are highlighted in Fig. 12.

The insulation ratio [12], [84], [83] is defined as the total thickness of the magnetic insulation typically air in the q-axis with respect to the total thickness of the rotor lamination as

$$k_{\mathrm{air}} = \frac{\sum_k hc_k}{R_{\mathrm{ro}} - R_{\mathrm{sh}}} \tag{7}$$

where R_{ro} is the rotor radius, R_{sh} is the shaft radius, and hc_k is the barrier' thickness in the q-axis direction.

Fig. 12. ***Sketch of typical SynRM geometries with highlighted key geometrical parameters [84].***

Fig. 13. ***PM insertion: SynRM to PMaSynRM [85].***

An analytical model was developed in [85] to study the effect of the SynRM rotor geometry on the torque harmonic. Various automated optimization techniques were studied in [86]. The multiobjective genetic algorithm (MOGA), the multiobjective differential evolution (MODE), and the multiobjective simulated annealing (MOSA) were evaluated considering two objectives: torque ripple and average torque. It was identified that MODE gave the best results with a less computational burden. In [2], a sensitivity analysis of torque ripple reduction was performed on SynRM and PMaSynRM. It was shown that a small variation in rotor geometry can cause a high torque ripple. A single objective optimization (SIMPLEX) was carried, and the optimal solution was further studied at different current ratings.

Indeed, the torque ripple is one of the key drawbacks of the SynRM topology; however, it has been shown that it can be effectively addressed by applying various design optimization techniques. There are various examples in key journal publications showing that torque ripple can be minimized up to values lower than 15% [75], [2], [63], [86].

E. PM Assistance

PM assistance is the main design leverage to improve the SynRM PF [12], [61], [63]. A single PM piece, usually ferrite, is inserted into the rotor flux barrier central segment, as shown in Fig. 13 [85].

A PM insertion results in the reduction of L_q (1), as the PMs tend to saturate the iron bridges, ribs, and the obvious increase in PF as the presence of the PM's flux linkage compensates for $L_q I_q$, as shown in Fig. 14.

The PF improvement leads to a reduction of the required volt–ampere rating of the power electronics converter with significant cost savings. Moreover, PM assistance will improve an FW capability as it was highlighted in [12]. By solving the phasor diagram (see Fig. 14), the FW capability can be increased if the ratio between q-axis inductance and PM flux follows the relation (8) [48]

$$\frac{L_q I_q}{\Lambda_m} \geq 1 \tag{8}$$

where Λ_m is PM flux linkage, as shown in Fig. 14.

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Fig. 14. ***Phasor diagram of PMaSynRM.***

In addition, the use of ferrite magnets does not significantly affect the motor cost because of its low price, about 3.4 EUR/kg [12].

F. Homothetic Design Scaling Principle

One of the recent advancements in the design methods for SynRM makes use of the homothetic scaling criteria. It has been proven that this approach is useful as a preliminary design technique when sizing a wide range of machines [84], [87].

In [84], the design scaling principle was validated for a wide range of machines. The main idea is that, starting from an optimized SynRM geometry for a specific power rating, a wide range of other machines for different power ratings can be obtained by simply scaling the original optimal geometry. An example of scaled SynRM geometries is presented in Fig. 15.

The behavior of the derived machines was studied using the methodology presented in [83], allowing to identify interpolating functions that correlate the machine sizes with its performance. Power regression (PWR) and polynomial regression (PLR) methods were used to derive the following general equation:

$$T\left(R_{\mathrm{si}}, \gamma\right) = p_0 + \sum_{k,j} a_k R_{\mathrm{si}}^k + b_j \gamma^j + c_{k,j} R_{\mathrm{si}}^k \gamma^j \tag{9}$$

where R_{si} is the stator inner diameter; a_k, b_j, and $c_{k,j}$ are the ith- and jth-order specific PLR coefficients. Similarly,

Fig. 15. ***Scaled SynRM M21 and M22.***

Fig. 16. ***(a) M21 and (b) M22 SynRM experimental rigs [83], [87].***

the constant torque curves on the (i_d, i_q) plane were generalized with respect to ampere-turns as follows:

$$T_{\mathrm{p.u.}}\left(\mathrm{mmf}_d, \mathrm{mmf}_q\right) \sim \sum_{k,j} a_k \mathrm{mmf}_d^k + b_j \mathrm{mmf}_q^j + c_{k,j} \mathrm{mmf}_d^k \mathrm{mmf}_q^j \tag{10}$$

where mmf_d and mmf_q are the d- and q-axis magnetomotive forces, respectively, whereas $T_{\mathrm{p.u.}}$ is the per-unit torque value that is defined with respect to the torque value that occurs at the MTPA trajectory current phase angle of $\alpha^e = 60°$ as

$$T_{\mathrm{p.u.}} = \frac{T\left(\mathrm{mmf}_{s1}, \alpha^e\right)}{T\left(\mathrm{mmf}_{\mathrm{ref}}, 60^o\right)} \tag{11}$$

where mmf_{s1} is the stator fundamental magnetomotive force and $\mathrm{mmf}_{\mathrm{ref}}$ is the reference magneto motive force for MTPA excitation current $\alpha^e = 60°$.

The proposed functions (9) and (10) were validated experimentally on two machines that were derived from the similar geometry both having a four-pole 48-slot combination labeled as M21 and M22 Fig. 16. M22W is a derived machine that was scaled radially by a factor of $S_{\mathrm{si}} = 1.23$ with respect to the original geometry M21.

Fig. 17 presents the constant torque curves comparison of the derived with the interpolating function (10). As can be observed, both machines have a very similar torque pattern, which confirms the proposed scaling design approach.

In [84], the effect of homothety was also evaluated in terms of torque ripple. Two general sizing approaches based on the homothetic scaling principles were defined and evaluated. It was shown that the rotor parameters converge to the same per-unit values for all the scaled geometries. It was shown that the FE design stage can be greatly simplified by considering novel dimensioning techniques.

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Fig. 17. *Comparison of constant torque curves on (I_d, I_q) [87]. (a) T_{M21} (I_d, I_q). (b) T_{M22} (I_d, I_q).*

G. High-Speed SynRM

High-speed (HS) SynRMs have attracted ever-increasing research interest in the last decade. The key publications in that matter are [88]–[94].

A comprehensive study of the HS-SynRM was performed in [90]; stator and rotor laminations are shown in Fig. 18. The HS-SynRM was designed in two stages considering electromagnetic and mechanical optimization.

It can be said that the key challenge for the HS applications is optimizing from both electromagnetic and structural points of view the rotor geometry in order to guarantee the integrity of the rotor at HSs and minimize the unwanted leakage flux caused by ribs thickening and so the related torque loss. In [89], a comparative design exercise of different rotors of HS-SynRM was presented considering both electromagnetic and structural aspects. The tradeoff between rotor geometrical complexity, optimal performance, and the computational burden was deeply investigated. The designed machine was manufactured and tested reaching 35 000 rpm. The efficiency is reported to be always above 80%.

In [93], a comprehensive design methodology for HS-SynRM has been introduced and validated against FEAs and experimental findings. Adopting the same design approach, di Nardo *et al.* [94] report a comparative design exercise in order to identify the optimal soft magnetic materials to be used for both stator and rotor of an HS-SynRM.

In [88], a two-pole SynRM (as shown in Fig. 19) with minimized eddy current losses was designed. The rotor was assembled of bonded segments of ferromagnetic and nonmagnetic steels. Experimental results proved to reach a 10 kW 10 000 rpm with 91% efficiency, whereas the rotor/losses had 0.5% of the total input power.

Fig. 18. *Stator and rotor laminations [90].*

Fig. 19. *HS-SynRM: rotor structured on the left-hand side and assembled rotor on the right-hand side [88].*

In brief, it can be said that SynRM has the potential for HS applications. The main challenge comes from the mechanical aspect, which was proven to be effectively addressed with a multiphysics design approach.

For the past three decades, there was a strong research push toward SynRM industrialization. A number of innovative design techniques were developed and successfully utilized to address the main design challenges of the topology. It can be concluded with confidence that the SynRM design no longer can be considered as a very complex procedure due to the research contribution. The design procedure has been "standardized" for the easiest and fastest way for the development of the optimal SynRM.

VI. SynRM POTENTIAL AS A MODERN INDUSTRIAL EM

In order to better understand the potential of SynRM technology, a detailed comparison with SCIM and PM machines is hereafter reported highlighting advantages and drawbacks.

A. SynRM Versus SCIM and SynRM Versus PM Machines

A common design practice for the SynRM is to use the stator of SCIM and simply substitute the rotor. In [95], it was shown that approximately 80% of torque can be retained, whereas the losses were reduced down to 60% of the initial design adopting this design approach making the SynRM a valuable alternative for industrial application [96]. The SCIM has been serving as the *industry's workhorse* for over a century. High-efficiency SynRM is a competitive technology that could be a replacement for SCIM in many applications. The following SynRM advantages over SCIM can be highlighted [95], [96]:

1) synchronous operation—no slip and synchronous drive;
2) no conductors in rotor;
   a) robustness;
   b) manufacturing cost;

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c) fewer rotor losses;
d) "cold" rotor;
e) lower maintenance requirements.

3) higher efficiency;
4) potentially higher power density within the same frame size;
5) lower rotor inertia;
6) longer bearing life.

Main improvements with respect to SCIM come from the fact that SynRM has no conductors in the rotor, which brings many benefits from design and maintenance points of view. In general, it is estimated that approximately 25% of total losses in SCIM is coming from the rotor. It is well known that, in any EM, the rotor is the most difficult part to cool. Hence, this leads to the conclusion that the SynRM is a "cold rotor" machine [10], [78]. The majority of SynRM losses are generated in the stator (copper losses), where the heat is generally easier to remove with classical finned frames. Nevertheless, along with the highlighted advantages, the disadvantages of SynRM with respect to SCIM can be highlighted as follows:

1) no line-startup capability (unless considering line-start SynRM);
2) lower PF [68];
3) complex control;
4) not yet widely accepted by industry.

Comparing PM synchronous machines and SynRM, both have similar operation principles and do not contain any rotor conductors. Hence, the rotor losses are reduced compared to SCIM. However, the rotor's field is produced by PMs that can be the source of other losses (i.e., eddy current losses in the PM). There is no doubt that the PM machines have superior torque density. However, there are a number of advantages of SynRM over PM machines:

1) no PM;
   a) significantly reduced cost;
   b) significantly reduced embedded carbon;
   c) easier assembly and manufacturing;
   d) significantly reduced risk of overvoltage;
   e) reduced risk in the supply chain.
2) robustness (no PM demagnetization risk);
3) wider operating speed range;
4) no need for a disengagement mechanism (clutch) in the case of short-circuit faults.

Lack of PMs is the main advantage of the SynRM, which brings a lot of benefits. Apart from cost reduction and manufacturing benefits, such as reduced embedded carbon (skipping PM manufacturing stage), the lack of PMs in the rotor eliminates the risk of overvoltage. It can occur in the FW operation at a higher speed. In the case of control loss, back EMF generated by the motor at a higher speed can easily damage the inverter [97].

Nevertheless, the PM machines still have obvious advantages over SynRM. SynRM is expected to have the following:

Table 2 Qualitative Cost Comparison [100]

Raw Materials Properties				
Raw material	Mass density [kg/m^3]		Cost [$/kg]	
Ferromagnetic steel (M470-35A)	7650		1.67	
Cu bars	8900		9.23	
Al bars	2950		4.55	
Ferrite PMs	4800		3.28	
Weight [kg]				
Component	Rotor type			
	SCIM (Cu)	SCIM (Al)	SynRM	PMaSynRM
Rotor lam.	0.701	0.701	0.679	0.679
Cu bars	0.673	-	-	-
Al bars	-	0.278	-	-
Ferrite PMs	-	-	-	0.058
Total weight	1.374	0.979	0.679	0.737
Cost [$]				
Component	Rotor type			
	SCIM (Cu)	SCIM (Al)	SynRM	PMaSynRM
Rotor lam.	1.17	1.17	1.14	1.14
Cu bars	6.22	-	-	-
Al bars	-	1.27	-	-
Ferrite PMs	-	-	-	2.41
Rotor cost $	7.39	2.44	1.14	3.55

1) lower power density and torque density;
2) lower PF;
3) increased VA ratings;
4) nonconstant power speed range.

Considering the example of the ABB's product line that includes SCIMs and PM motors, as well the SynRM, the SCIMs are capable to meet the IE2–IE4 Standards up to 1200 kW. The PMs are mainly aimed for higher torque dense solutions up to 2500 kW, whereas the SynRM is aimed to fill the gap in performance and efficiency between conventional SCIMs and PM machines [19], [32]. The main advantages of the SynRM that are listed by ABB are lack of any rotor excitation (no winding or magnets) and the service-friendliness respect with SCIMs as there are no magnetic forces in the rotor. One of the most recent advancements according to Fanning [32] is the new IE5 SynRM drives. These motors meet the requirements of the IEC 60034-30-2 and are produced for a power range between 5.5 and 315 kW.

Several advantages of SynRM over SCIMs and PM machines were discussed by Spargo [10], Pellegrino *et al.* [12], and Kamper [98]. In summary, SynRM has higher efficiency compared to SCIM and significantly lower prices compared to PM machines due to the lack of rare-Earth materials. Considering a rotor with no conductors and PMs translates into better robustness and fewer losses. Also, it has a noticeably

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Table 3 Summary of the Steady-State Performance of LS-SynRM and SCIM [104]

Parameter	LS-SynRM1	LS-SynRM2	LS-SynRM3	SCIM
Line voltage [V_{rms}]	398	398	398	398
Phase Current [A_{rms}]	5.8	4.79	4.95	5.0
Continuous Torque [Nm]	14.2	14.2	14.2	15.1
Rated Speed [rpm]		1500		1381
Rated Power [W]	2231	2231	2231	2183
Rated PF	0.718	0.763	0.745	0.794
Joule loss, stator [W]	439	299	318	330
Joule loss, rotor [W]	121	31	48	168
Efficiency [%]	77.3	84.5	83.4	79.0

wider speed range compared to the PM machine [99]. Therefore, SynRM is a promising alternative to SCIMs and PM machines. The biggest challenges can be highlighted as high torque ripple and lower PF also due to the iron ribs required for mechanical retention [90].

B. Qualitative Cost Comparison

A qualitative cost analysis of SCIM, PMaSynRM, and SynRM has been reported in [100]. The comparison was carried out for the same stator frame and slot/pole combination. Four different motors were considered: SCIM with copper and aluminum bars, and SynRM and PMaSynRM machines with the ferrite PMs. The comparison includes the price of the raw materials only, which was provided by manufacturers partners and does not include the cost of the manufacturing.

The comparison was carried out under assumptions that all four motors have the same stator geometry and nonactive electromagnetic components, such as shaft, bearings, and housing parts. In this example, the M470-35A electrical steel was used in accordance with the EU Standard EN 10106 [101].

Table 2 summarizes the comparison in terms of weight and cost of the raw material, including the price in $/kg as of April 2021. It is important to outline that the specific cost of materials will vary depending on the manufacturer.

Based on the summary of Table 2, the SynRM rotor is the cheapest topology as it is essentially "one iron piece" rotor. The PMaSynRM is approximately three times more expensive due to the additional cost of ferrite PMs. Nevertheless, considering the benefits that are brought by PM insertion, as it was discussed in Section V-E, it can be a valuable solution for certain applications. The copper bar SCIM (Cu) topology has a significantly increased price compared to the other alternatives, whereas the aluminum bar SCIM (Al) has a two-time cost of SynRM.

To conclude, the SynRM rotor has a reduced price compared to the other main contenders; therefore, it represents the most economical option for large-scale industrial production.

C. Line-Start SynRM

A direct-on-line topology of SynRM or line-start SynRM (LS-SynRM) has been widely developed for many applications, such as fans, compressors, and pumps [102]–[105].

Fig. 20. ***LS-SynRM rotor topologies [104].***

Fig. 21. ***Losses and motor efficiency of the ABB's 37-kW SCIM and the equivalent SynRM at rated conditions (SynRM highlighted with blue and SCIM highlighted with black).***

Fig. 22. ***SCIM and SynRM efficiency based on ABB's data, 2014.***

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Fig. 23. ***SynRM process performance motors that are available on the market as of December 2020. All machines are presented at rated speed and rated power.***

One of the main reasons that LS-SynRM is getting wide attention is the ability to line-start just like SCIM without the need of an inverter. Also, the secondary copper losses of SCIM can reach up to 25% of total losses [102]. Therefore, LS-SynRM is a perfect candidate to replace standard SCIM.

In [103] and [104], a full comparison of three different LS-SynRMs with SCIM was presented. Rotor topologies of LS-SynRM had different approaches in barrier and rotor cage positions, as shown in Fig. 20. As can be observed, SynRM flux barriers were filled with aluminum (dark gray). These three LS-SynRM topologies were tested in comparison with the equivalent SCIM. The summary of the steady-state performance at rated conditions is shown in Table 3, where LS-SynRM1 is shown in Fig. 20(a), LS-SynRM2 is shown in Fig. 20(b), and LS-SynRM3 is shown in Fig. 20(c)

As can be observed, LS-SynRM2 and LS-SynRM3 have higher efficiency in comparison with LS-SynRM1 and SCIM, which is mainly due to reduced Joule losses at the rotor. However, all LS-SynRM machines have lower PF in comparison with SCIM, which can be addressed by introducing ferrite PMs [12], [104].

VII. INDUSTRIAL ACCEPTANCE

In summary, the SynRM industrial acceptance has been steadily increasing over the last two decades as the main alternative to conventional SCIM.

A full product range of SynRMs is announced at a German motion control show in November 2012 by ABB [19]. Currently, their high-efficiency SynRM products range from 5.5 to 350 kW. Considering the machine design, SynRM can be sized for the exact same frame as an equivalent SCIM; however, the achieved efficiency will meet the IE4 efficiency or even IE5. The same frame size SynRM can reduce the losses while delivering the same or higher power, which was demonstrated by ABB's offering [106]. These machines reduced in size, having higher rated power, and increased efficiency with respect to their SCIM counterpart.

Fig. 21 presents the losses comparison of the existing ABB's 37-kW rated SCIM in black and SynRM in blue. As can be observed, the SynRM efficiency reduction meets the IE4 Standard with 95.3% efficiency, whereas the SCIM having a 92.7% efficiency falls under the IE2 Standard. The loss reduction for this motor example leads to 1.1-kW power saving considering 8760 h of operation, and having an average price of 0.15 EUR/kWh leads to 1445 EUR/year savings.

To illustrate the superiority of the SynRM IE4 that is marketed by ABB, Fig. 22 is presented. The relative package efficiencies are depicted [19] (considering motor and inverter losses) over the offered rated power range for both SCIM and SynRM. Both SynRM and SCIM drives are at rated torque and speed, and self-cooled; all machines have four poles and 50 Hz, and are controlled by the ACS850 drive using sensorless direct torque control.

As of December 2020, several EU motor manufacturers are already venturing toward the SynRM machines. Fig. 23 presents the SynRM line-ups of the key manufacturers as of December 2020 based on the data gathered from [19], [20], and [105]–[107]. All manufacturers have various drives that meet the IE2–IE5 Efficiency Standards. Bonfiglioli is currently producing IE2–IE4, lower rated machines that are rated at both 1500 and 3000 rpm. They have different efficiencies for machines rated up to 18.5 kW. Wonder is another SynRM manufacturer that has

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a wider range of SynRM line-up starting from 0.55 up to 45 kW for two rated speed options: 1500 and 3000 rpm. All machines are claimed to meet the IE4 Standard. Siemens currently has a very similar SynRM line-up to Wonder from 0.55 up to 45 kW that meets the IE4 Standard.

The two biggest manufacturers are KSB REEL and ABB, and they cover a very wide range of SynRM that can meet different efficiency standards. KSB REEL is dominant at lower ratings from 0.55 up to 18.5 kW, as claimed by the manufacturer these machines meet the Gold Standard IE5, whereas ABB has the IE3 machines for lower ratings. ABB is dominant at the power range starting from 7.5 up to 315 kW as they have a variety of machines at different speed ratings: 1000, 1500, 2100, and 3000 rpm that meet IE3–IE5. KSB REEL has the biggest power-rated commercial SynRM products up to 450 kW.

In conclusion, it can be stated that SynRM has seen an increasing acceptance by the industry and will continue to grow due to several related benefits. ■

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