《高阶会员专属视频》-第11期

IEEE期刊论文导读，同步磁阻马达（SynRM）有何先天优势？为何可以取代感应电机？

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CONTRIBUTED PAPER

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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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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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].

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

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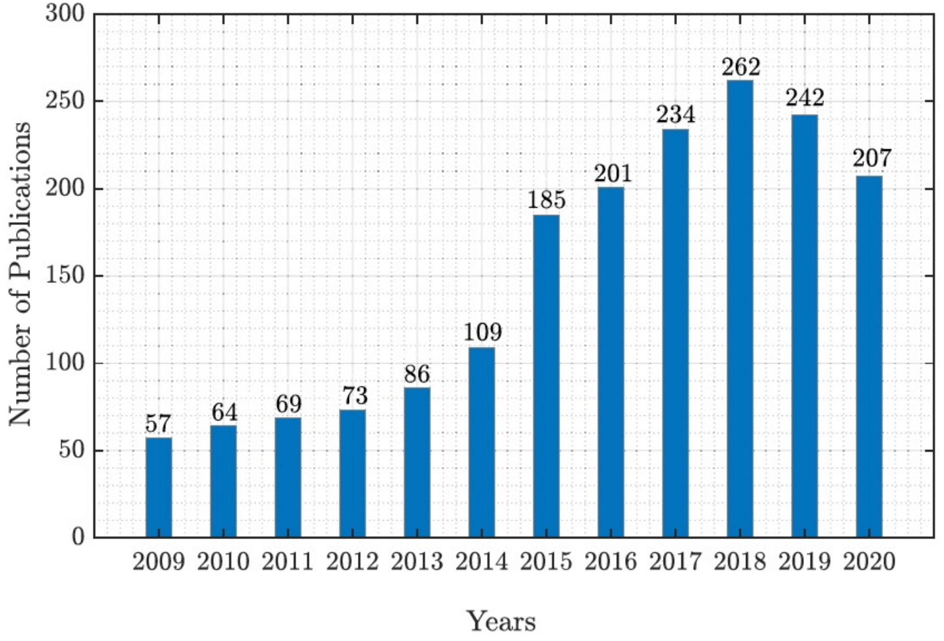

Fig. 1. ***Number of publications on SynRM topic over the past decade [1].***

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.

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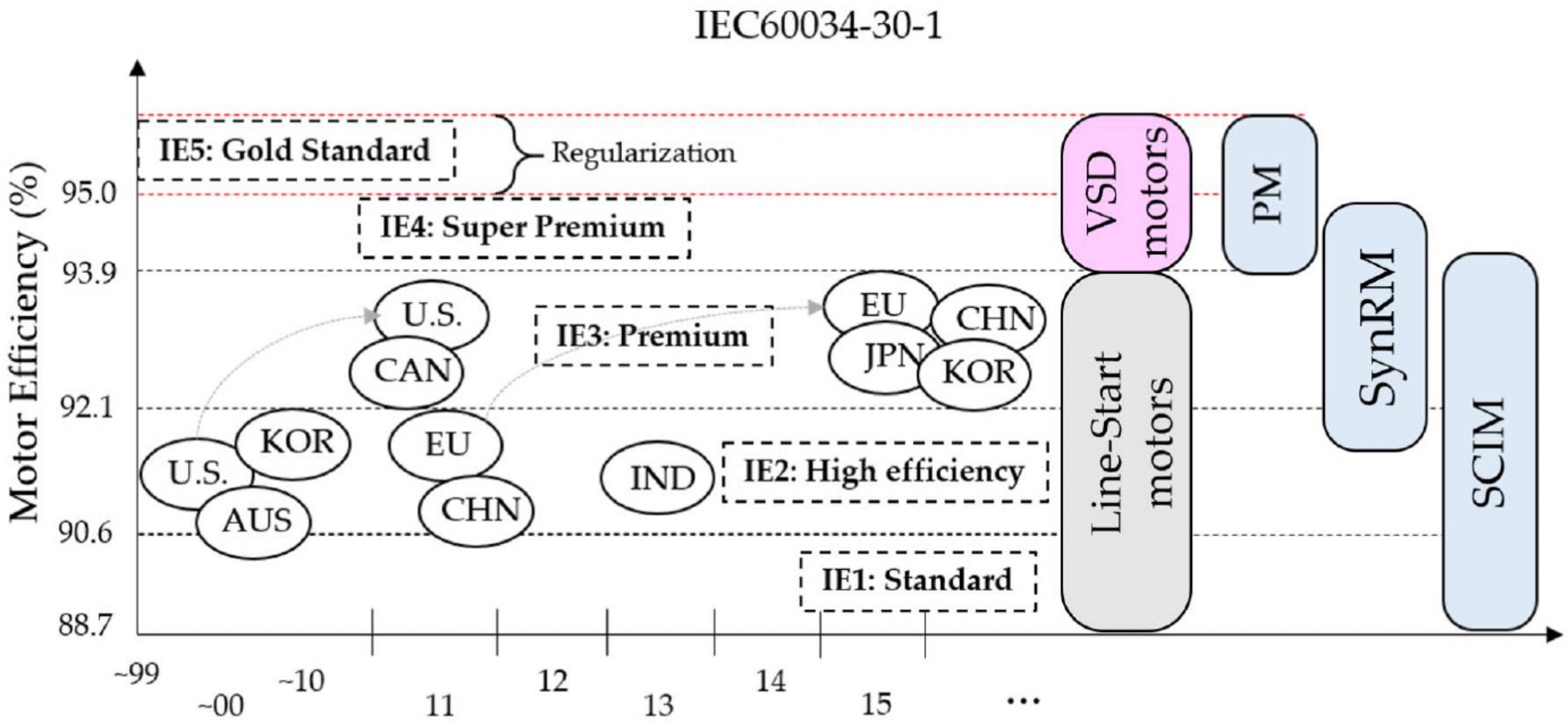

Fig. 2. *EM Efficiency movement timeline, standard 15-kW motor example [39].*

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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

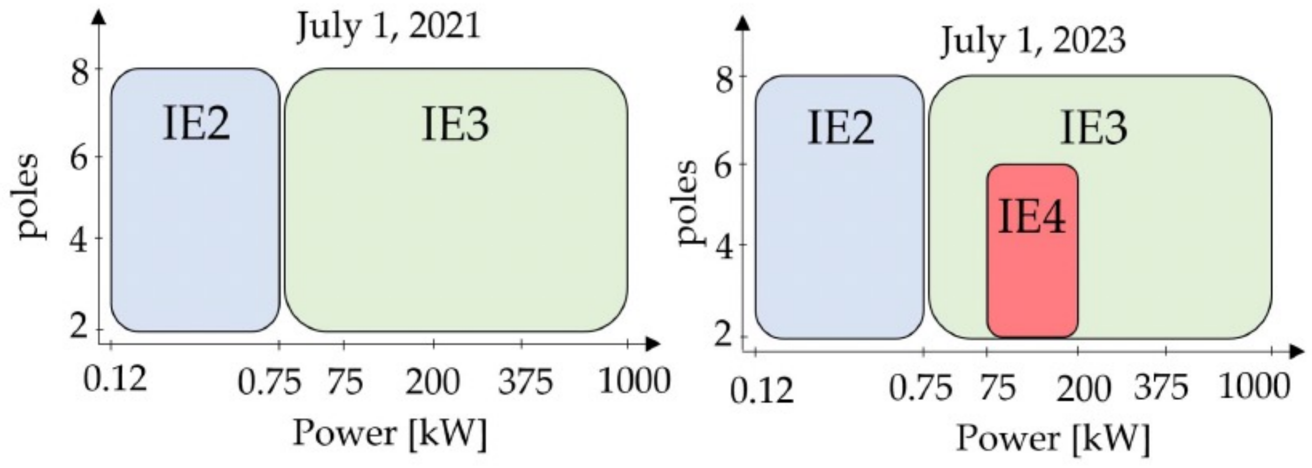

Fig. 3. ***Efficiency regulations 2021–2023.***

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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,

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

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

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

$$\xi = L_d / L_q. \qquad (2)$$