Power Factor-Based Energy Efficiency Approach in Synchronous Reluctance Motors

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Abstract

Nowadays increasing energy needs highlight the goals of high efficiency and low losses in electric motors. As an alternative to asynchronous motors, which are widely used in industry, synchronous reluctance motors (SynRM) are attracting attention for their low cost and high efficiency. In this study, an approach is presented that considers the power factor as the primary optimization criterion. This paper comprehensively reviews the methods presented in the literature for improving the power factor in SynRM systems. Approaches such as rotor design, arrangement of magnetic flux barriers, hybrid models, and control strategies are discussed in relation to the power factor's impact on energy efficiency. The literature review reveals that power factor-focused improvement strategies have significant potential to enhance SynRM performance and reduce energy losses. This study presents electromechanical performance, loss, and magnetic loading analyses for a SynRM designed using Motor-CAD. The study also discusses torque ripple, power factor, and optimization recommendations.

Keywords: Synchronous Reluctance Motor, Power Factor, Energy Efficiency, Rotor Design

1. Introduction

1.1. Synchronous Reluctance Motors

Synchronous reluctance motors (SynRMs) have gained significant attention in academic and industrial circles in recent years due to their simple rotor structures, low cost, and lack of need for rare earth elements. These machines, which do not have magnets or windings in their rotors, can only generate torque based on the difference in magnetic reluctance, thus eliminating rotor copper losses and providing reliability and efficiency [6]. Compared to traditional asynchronous motors, SynRMs of the same size can achieve higher levels of energy efficiency (IE4–IE5 class), making them particularly advantageous in variable-speed applications such as pumps, fans, and compressors [7]. Additionally, SynRMs offer suitable solutions for electric vehicle auxiliary systems and renewable energy-based generator systems that do not require high torque density [8].

The performance of these machines is directly related to rotor geometry. By creating different magnetic reluctance paths along the d-axis and q-axis on the rotor, the saliency ratio (Ld/Lq) is increased, thus making higher torque production possible [9]. Recent studies have shown that power factor and efficiency can be improved simultaneously with advancements in rotor design [10,11].

1.2. Power Factor (PF)

In electrical machines, the power factor is defined as the ratio of active power drawn from the grid to apparent power, and it is considered a critical performance indicator for both energy efficiency and system stability. A low power factor causes more reactive power to be drawn from the grid, which in turn increases the capacity requirements of inverters and supply systems [12]. Although synchronous reluctance motors (SynRMs) structurally have a low power factor due to the absence of magnets or windings in their rotors, this disadvantage can be significantly reduced with appropriate rotor design and advanced control methods [13]. Indeed, by optimizing the number of rotor barriers, the bridge structure, and the barrier positions, the saliency ratio can be increased, thus leading to a significant improvement in the power factor [14]. Additionally, various control approaches such as online maximum power factor search (MPFSC) algorithms [12] and dual-ended inverter systems [17] have been proposed in the literature to improve the power factor. In this context, increasing the power factor not only improves energy efficiency but also allows for the use of smaller inverters, reducing the overall system cost [15].

$$cos\varphi \approx \frac{1}{\sqrt{1+\left(\frac{L_q}{L_d}tan\theta\right)}} \tag{1}$$

Equation 1 includes the power factor expression. Θ is the current angle. One of the fundamental determinants of performance is the d-axis and q-axis inductance values of the rotor. The d-axis inductance (L_d) is the inductance value in the direction where the magnetic flux follows the path of least reluctance across the rotor barriers, meaning the flux passes easily, and is generally high. In contrast, the q-axis inductance (L_q) is the inductance value measured in the high-reluctance direction where the magnetic flux is blocked by barriers, and it is at a relatively low level. The power factor improves as the ratio of L_d/L_q increases. This equation will be the fundamental mathematical basis for the power factor-based efficiency approach, which is the original contribution of your work.

$$\xi = \frac{Ld}{Lq} \tag{2}$$

Another parameter that directly determines the performance of SynRM is the saliency ratio. The formula for the saliency ratio is given in Equation 2.

1.3. Energy Efficiency

Today, energy efficiency has become one of the most important design criteria, both for reducing costs in industrial motor applications and for ensuring environmental sustainability. Electric motors account for over 40% of global energy consumption, and even small improvements in the efficiency of these machines can lead to significant gains in total energy consumption [7]. Synchronous reluctance motors (SynRM) have high efficiency potential due to their ability to eliminate copper losses in their rotors and their simple structure. Studies have shown that with the correct rotor geometry and appropriate control strategies, the highest energy efficiency classes, such as IE4 and IE5, can be achieved [7,9]. Additionally, advanced optimization techniques such as harmonic current injection [10] and artificial intelligence-based control methods [9] can minimize copper and iron losses, thereby improving the overall energy performance of the motor. However, improving the power factor also has a direct impact on energy efficiency, contributing to the overall efficiency of the system by reducing inverter losses [6,12].

1.4. Literature Studies

There are numerous studies in the literature on improving the performance of synchronous reluctance motors. In these studies, approaches focused on rotor design, power factor, and efficiency have come to the forefront. For example, in a study on rotor optimization with a fractional slot winding structure that can achieve the IE5 energy efficiency class, low torque ripple and high efficiency were achieved [7]. On the control strategies side, prominent approaches include minimizing losses through active flux adjustment [4], accounting for magnetic saturation and iron losses using artificial neural networks [9], and online maximum power factor search algorithms [12]. Additionally, it has been shown that efficiency is increased by harmonic current injection in concentrated-wound SynRMs [10] and that dual-ended inverter drives improve the power factor and constant power speed ratio [17]. In addition, there are studies that have improved the power factor and synchronization capability in line-start SynRM designs by optimizing the number of rotor barriers and the bridge structure [11,13]. In recent years, research on permanent magnet-assisted SynRMs has shown significant improvements in efficiency and power factor, while also considering cost-performance optimization [16,18].

2. Power Factor and Its Impact on Energy Efficiency

Power factor is one of the most critical parameters determining the performance of electric motors. A low power factor causes an increase in the current drawn from the grid, which leads to higher copper losses and reduced system efficiency. Additionally, low power factor negatively impacts capacity utilization in the power distribution network, increasing the need for reactive power compensation.

In Synchronous Reluctance Motors (SynRM), efficiency is directly related to the rotor structure and magnetic flux paths, and improving the power factor can significantly increase the motor's overall energy performance. Studies in the literature show that an increase in power factor not only reduces losses but also positively affects performance indicators such as the motor's torque density and constant power range. Therefore, power factor stands out as a fundamental optimization criterion to be considered in energy efficiency-targeted SynRM designs.

2.1. Mathematical Basis: Power Factor–Efficiency Relationships

In a three-phase drive, the apparent power S and copper loss P_{cu} are expressed as follows:

$$S = \sqrt{3}V_{LL}I,\ P = \sqrt{3}V_{LL}I \times PF,\ P_{cu} = 3I_{rms}^2R_s \quad (3)$$

From this, it can be seen that for the same shaft power P and line voltage V_{LL}, the current I is inversely proportional to $I = \frac{P}{\sqrt{3}V_{LL}\times \mathrm{PF}}$; therefore, as the power factor increases, the current and the associated copper loss decrease, and the overall efficiency increases $\left(\eta = \frac{P_{\mathrm{out}}}{P_{\mathrm{out}}+P_{\mathrm{cu}}+P_{\mathrm{core}}}\right)$ [14,15]. This relationship directly affects the apparent power sizing of the inverter, particularly in SynRM drives targeting the IE4–IE5 efficiency class; a higher power factor results in lower inverter current and smaller apparent power requirements [1,7,15].

In SynRM, the electromagnetic torque in terms of d–q axis currents and inductances is:

$$T_e = \frac{3}{2}p\left(L_d - L_q\right)i_d i_q = \frac{3}{4}p\left(L_d - L_q\right)I^2 sin(2\gamma) \quad (4)$$

(where I is the stator current magnitude, γ is the current vector phase angle) [14,15]. Equation 4 shows that the current required for the same torque is inversely proportional to $(L_d - L_q)$ and $sin(2\gamma)$; therefore, designs that increase the saliency ratio $\xi = L_d/L_q$ provide a smaller current and thus a higher power factor for the same torque [14,19,20]. When Equations 3–4 are considered together, the PF increase reduces P_{cu} and decreases the inverter's apparent power requirement; this effect improves both motor and driver efficiency [6,15,17]. The effect of the γ angle on the PF and current components via the phasor diagram is summarised In Fig. 1 [15].

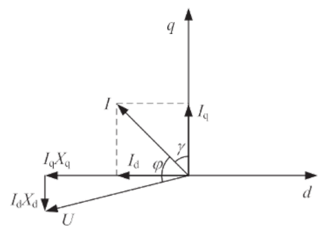

Fig. 1: SynRM at the point of reference: phasor diagram and the effect of the γ angle on PF [15].

Furthermore, the effective efficiency model, which includes saturation and iron losses, demonstrates the strong dependence of the $\eta(P_{\mathrm{cu}}, P_{\mathrm{core}})$ function on current amplitude and flux harmonics; reducing the current and suppressing flux harmonics simultaneously increases PF and efficiency [8–10]. Therefore, the power factor is a determining parameter for efficiency not only from the grid perspective but also in terms of the magnitude of magnetic losses and torque/current efficiency [2,9,10].

2.2. Effect of Rotor Geometry and Electromagnetic Parameters on Power Factor

PF in SynRM is shaped by the magnetic circuit design that determines L_d and L_q, primarily the rotor flux barrier geometry; multi-layered/multi-part barriers produce high L_d and low L_q, while bridge thickness and barrier placement are decisive on ξ [19,20]. The literature reports that barrier geometries optimised with fractional-slot windings provide IE5 class efficiency and increased power factor, with reduced torque ripple [7]. Asymmetric barrier and thin bridge designs improve PF by reducing leakage current and increasing saliency; thus, the required current for the same torque decreases and copper loss decreases according to Equation 3 [11,13,20]. The expected increase in PF with the increase in saliency ratio is shown in Fig. 2 [14].

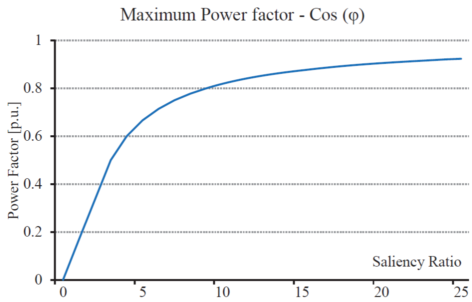

Fig. 2: Change in maximum power factor with L_d/L_q (saliency) [14].

In the line-start (LS-SynRM) variants of SynRM, parametric analyses determining the operating point (number of turns/slots, package size, barrier pattern) were used to optimise the PF–efficiency balance; experimental validations demonstrated both PF improvement and loss reduction [11,13]. The effects of parameter conditions (load profile, speed, material selection) on PF and efficiency across the full load range were examined in detail; under some conditions, the improvement in PF was shown to directly increase system efficiency [5,11].

The design trade-offs of the PF–torque density–saliency triad have been clarified in the literature: the MTPA angle maximises torque/current efficiency, while the MPF angle minimises the inverter's apparent power; optimum operation is achieved by adjusting γ according to the application requirement [14,15]. Specifically, in [15], by changing the number of winding turns and stack length, the rated current was reduced and the power factor was increased, and its effects on efficiency and inverter matching were verified [15].

2.3. Driver/Control and Hybrid Approaches: Dynamic Optimisation of Power Factor

PF can be enhanced not only through design but also through control strategies. Current-angle-based online maximum power factor search (MPFSC) continuously optimises γ during speed/load changes, reducing the reactive component and improving the inverter's apparent power utilisation [12]. The Maximum Efficiency per Ampere (MEPA) approach shifts the PF–efficiency trade-off to system-level optimisation by jointly minimising motor and inverter losses [6]. Optimal flux/current operation with active flux control (robust model-based) reduces losses even in saturation regions and supports PF [4].

In artificial intelligence-supported (ANN-based) optimum efficiency control, cross-saturation and iron losses are modelled, and current vector decisions are updated to increase PF and efficiency simultaneously; this contributes to the effective use of the $sin(2\gamma)$ term in Equation 4 and to the reduction of current amplitude [9]. Harmonic current injection (particularly 6th harmonic d–q current components) dampens flux harmonics arising from inductance harmonics, reducing iron losses and back EMF; the increase in copper losses due to injection is balanced by additional torque production, resulting in effective PF/efficiency improvement [10].

A double-ended structure can bring the PF seen by the source close to 1 by providing reactive power compensation with a second inverter and capacitive bank; as a result, the CPSR (constant power speed ratio) widens and the inverter utilisation rate improves [17]. Efficiency strategies developed by including saturation in generator mode (SynR generators) also increase overall energy performance by controlling PF/reactive power flow [8]. The two-converter and capacitive bank structure is shown schematically in Figure 3 [17].

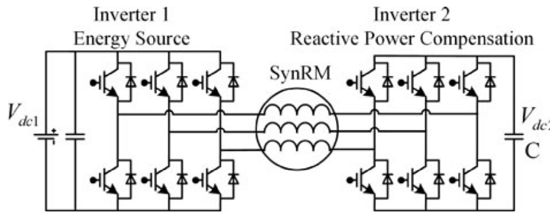

Fig. 3: Double-ended SynRM driver: source inverter + load-side inverter/capacitor bank to achieve PF≈1 [17].

3. Approaches to Power Factor Improvement in the Literature

Several studies have investigated different methods to enhance the power factor of Synchronous Reluctance Motors (SynRMs). These methods can be broadly categorized into rotor design-based approaches, control and drive strategies, and hybrid motor structures.

3.1. Rotor Design-Based Methods

The geometry and arrangement of flux barriers in the rotor play a decisive role in the power factor. Optimized barrier shapes reduce leakage flux and increase the saliency ratio, which directly improves the power factor. Matsuo and Lipo (1994) demonstrated that multi-layer flux barrier designs significantly enhance power factor and torque performance [19]. More recent studies have focused on asymmetric flux barriers and thinner bridge structures, showing improvements in efficiency and reduced torque ripple [20]. The synchronisation window associated with PF in LS-SynRM can be explained via the slip–torque curve in Fig. 4 [13].

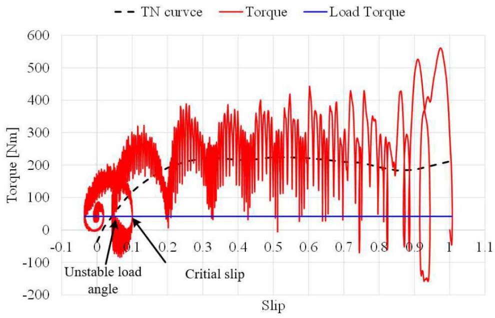

Fig. 4: LS-SynRM slip–torque curve showing the synchronisation process [13].

3.2. Control and Drive Strategies

In addition to rotor geometry, control strategies are crucial for power factor enhancement. D–q axis current control and loss-minimization algorithms have been widely applied. Optimization techniques such as Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) are reported to achieve optimal current settings for improved power factor and efficiency (Tawfiq et al., 2022) [21]. These approaches reduce reactive power consumption while maintaining torque capability.

Simulation and experimental studies have shown that considering the power factor as an optimization criterion has a direct impact on the performance of SynRM.

3.3 Hybrid Motor Approaches

The Pma-SynRM rotor architecture, where the PMs are placed at the innermost barrier, increases saliency and power factor by reducing L_q (Fig. 5) [18]. A growing trend in the literature is the development of Permanent Magnet-Assisted SynRMs (Pma-SynRMs). By integrating small amounts of permanent magnets, these hybrid motors achieve higher saliency ratios and improved power factor without excessive magnet usage. Wu et al. (2017) reported that PM-assisted designs provide a balanced trade-off between efficiency, torque density, and power factor [20].

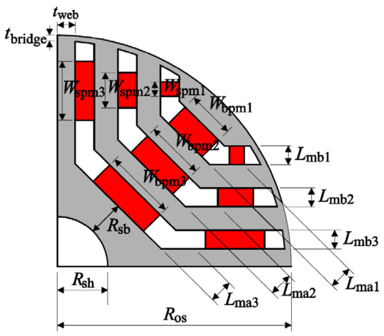

Fig. 5: Typical rotor cross-section for Pma-SynRM: magnets placed on the innermost flux barrier and the role of flux barriers on PF/saliency [18].

Overall, the literature demonstrates that both design optimization and advanced control strategies have notable impacts on improving the power factor of SynRMs, thereby contributing directly to enhanced energy efficiency.

4. Simulation Results

The graphs obtained from the simulation results are as follows. Looking at the simulation results, the RMS value of the current supplied to the machine is 5 A. As seen in Figure 6, the maximum and minimum values are 6.061 A.

Table 1. Initial Data

Parameter	Value
Stator Lam Dia (mm)	130
Stator Bore (mm)	85
Slot Number	36
Pole Number (2p)	4
Current (A)	4.5
Shaft Speed (RPM)	2000

The results obtained reveal that the designed motor provides continuity in electromagnetic torque production and exhibits efficient operating characteristics thanks to the sinusoidal shape of the current waveforms. Furthermore, it is observed that the design approach, which was carried out with the goal of achieving a high power factor, increases the energy efficiency of the motor. In this context, the proposed power factor-based energy efficiency approach confirms that it is an effective method for improving performance in synchronous reluctance motors.

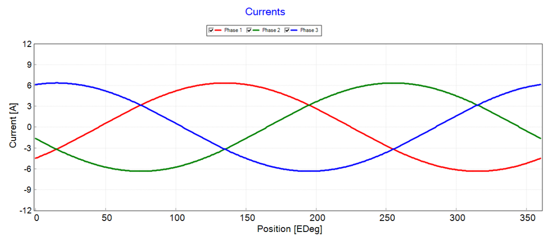

Fig. 6: Current position graph

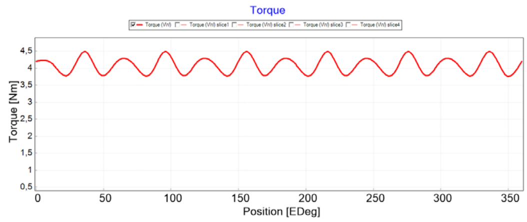

Fig. 7: Torque position graph

Looking at the torque graph in Figure 7, the generally smooth shape of the torque curve indicates that the motor is operating stably and that harmonic components are at a limited level. This result shows that the optimization made in the rotor geometry has balanced the magnetic flux density and significantly reduced the oscillations occurring in the electromagnetic torque.

Table 2. Developed Motor Data

Parameter	Value
Nominal Torque (Shaft) (Nm)	3.88
Output Power (W)	813.14
Efficiency (%)	85.19
Copper Loss (W)	101
Total Losses (W)	141.4
Armature Conductor Temperature (℃)	60.47
Power Factor	0.725
Torque Ripple (%)	16.4

However, obtaining the torque characteristic in a manner that supports the current profile designed with a high power factor target demonstrates that the proposed power factor-based energy efficiency approach has a positive effect on motor performance.

5. Conclusion

The studies examined consistently demonstrate that improving the power factor of SynRM has a direct and significant effect on overall energy efficiency. To summarize a few key findings, first, multi-layered and asymmetric flux barrier arrangements increase the clarity ratio and reduce leakage flux, leading to power factor improvements of up to 10-15% compared to traditional designs

[19,20]. Reducing bridge thickness further increases magnetic saturation, providing approximately a 3-5% increase in efficiency.

Control-oriented approaches such as d–q axis current optimization and loss minimization algorithms have resulted in improved reactive power management. Studies employing optimization techniques reported efficiency improvements of 2–4% while simultaneously achieving a higher power factor [21].

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