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PMSM Design for Elevators: Determination of the Basic Topology Affecting Performance

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Abstract: In recent years, with the increase in high-rise building construction, there has been a rise in demand for elevators. This demand has spurred mutual growth between the vertical transportation sector and high-rise building construction. Both sectors are improving technology, security, and comfort standards. Traditional elevator traction machines typically employ asynchronous motors coupled with geared reducers, despite their low energy efficiency and requirement for large machine rooms. However, with the proliferation of rare-earth magnet materials and advancements in driver technologies, the use of Permanent Magnet Synchronous Motors (PMSMs) in elevator traction machines has increased. PMSMs operate with direct drive, eliminating the need for reducers. High efficiency and passenger comfort are crucial parameters for elevator traction machines. This study focuses on identifying the fundamental topology that could influence the performance of PMSMs for gearless elevator machines. Factors such as stator materials, rotor structures, permanent magnets, winding configurations, slot/pole combinations, cogging torque and torque ripple have been examined to select suitable design topologies for elevator motors. Important topics such as the magnetic properties of grain-oriented silicon steel sheets used in stator construction, B-H curves, lamination forming and stacking factors have been addressed. Two different rotor topologies and magnet arrangements, namely internal and external, have been investigated in PMSM designs. Additionally, the use of four different magnet materials, namely AlNiCo, Ferrite, NdFeB, and SmCo have been compared for PMSM traction motors in elevators. Single-layer and double-layer winding configurations, distributed and concentrated winding configurations have been compared. Fractional slot/pole combinations, which directly affect the performance and comfort of PMSMs, have also been examined based on information obtained from the literature. Particularly, structures with high winding factors, such as 12/10, 12/14, 18/16, 18/20, 24/22, and 24/26 have been identified. Finally, studies on skewing to reduce cogging torque and torque ripple have been addressed.

Keywords: Permanent magnet synchronous motor, Elevator traction machines, Gearless machine, Topology, Permanent magnet

Introduction

Synchronous motors are electric motors where a magnetic synchronization is established between the stator and rotor. PMSMs emerged by replacing rotor windings found in synchronous motors with permanent magnets (PM). PMSMs generally offer higher efficiency because the magnetic field of permanent magnets results in lower iron losses and enables them to convert energy more efficiently. Additionally, in synchronous motors, there are rotor winding losses occurring in the rotor.

PM motors are often preferred in low-speed and high-torque applications (Pyrhonen et al., 2013). When elevator traction systems are examined, it is observed that PM motors are used without the need for a reducer system. Due to the low energy density of AlNiCo (Aluminum Nickel Cobalt) magnets, the initial PM motors were limited to small-sized and low-powered applications. However, recent advancements in rare earth elements and power electronics have provided new opportunities for PM motor design, manufacturing, and implementation. Large powerful PM motors can be used with both low-speed and high-speed drivers. (Gieras, 2010).

PM motors are widely preferred in the industry for elevator traction systems due to their advantages such as silent operation, high efficiency, long working life, high torque per unit volume, and high torque-speed characteristic (Soyaslan, 2020).

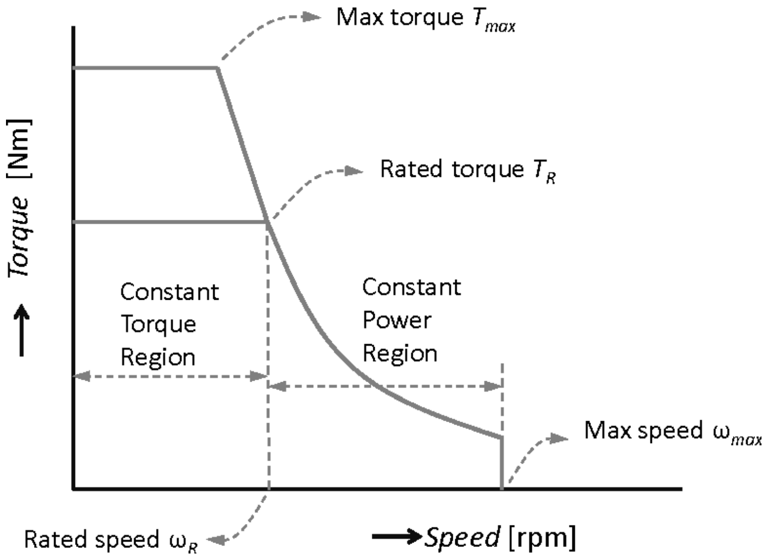


Figure 1. Torque-speed characteristic of PMSMs (Aydın, 2012)

Stator Design

PMSMs consist of the stationary part where the stator windings are wound. This part is formed by stacking and pressing silicon-coated steel sheets. Coating the steel sheets with silicon ensures insulation between the sheets. This minimizes eddy currents during operation and maximizes the magnetic properties of the sheets (Yıldız, 2009). The magnetic properties of grain-oriented silicon steel sheets are shown in Table 1.

Table 1. Magnetic properties of non-grain-oriented silicon steel sheets (Soyaslan, 2020)

Material	Sheet Thickness	Maximum Specific Total Loss at 50 Hz		Density
		Ĵ=1.5T	1.0T*	
		W/kg	W/kg	kg/dm3
M310-50A	0.50	3.10	1.25	7.65
M330-50A	0.50	3.30	1.35	7.65
M350-50A	0.50	3.50	1.50	7.65
M400-50A	0.50	4.00	1.70	7.70
M470-50A	0.50	4.70	2.00	7.70
M470-50HP	0.50	4.70	2.20	7.70
M530-50A	0.50	5.30	2.30	7.70
M530-50HP	0.50	5.30	2.30	7.80
M600-50A	0.50	6.00	2.60	7.75
M700-50A	0.50	7.00	3.00	7.80
M800-50A	0.50	8.00	3.60	7.80

The B-H curve, which expresses the relationship between magnetic field strength and flux density, defines the magnetic properties of a magnetic material. The portion of the curve following the knee region is called the saturation region. In the saturation region, increases in magnetic field strength result in only small increases in flux density. Therefore, the optimal operating point for motors is in the knee region of the B-H curve. That is, beyond the magnetic material's saturation point, the effect of flux density on performance decreases. Hence, motors are typically operated just below the saturation point to ensure efficient utilization of the magnetic material.

For prototype manufacturing of radial flux motors, silicon steel sheets are usually produced using cutting methods such as laser cut and wire erosion (Bayraktar, 2015). The cut sheets are stacked together with the aid of a mould and pressed with varnishing in between them. This process forms the stator lamination. The varnishing process helps in providing sound insulation between the stator sheets. During the cutting process, burrs and gaps between the sheets due to varnishing result in a usable stack length for the stator, defined as the stator stacking factor $\boldsymbol{k_{st}}$ generally ranges between (0.90-0.97) and is close to 1. Determining the value of $\boldsymbol{k_{st}}$ is important as it directly affects motor performance. The length of the pressed sheets determines the electromagnetic dimensions of the motor.

Rotor Design

The rotor is the moving part of a PMSM, consisting of laminations and magnets mounted on a shaft. The rotor typically contains a core made of pure iron or silicon steel sheets. Permanent magnets are arranged on this core to create a magnetic field in the air gap, with N-S poles facing each other. (Akar, 2010). These magnets provide the motor's magnetic field and interact with the current passing through the stator windings to drive the motor's rotation. The high energy levels and suitable sizes of permanent magnets positively impact motor performance. Some advantages of these magnets include increased induced electromotive force (EMF), reduced line current, decreased thermal load on the rotor and input power, increased power factor and maximum output power of the motor (Eker, 2017).

Today, the most commonly preferred structure for permanent magnet motors is the one where magnets are located on the surface of the rotor. Surface-mounted (SM) motors typically have magnets magnetized radially. Neodymium Iron Boron (NdFeB) rare earth magnets with low magnetic permeability (μr= 1-1.2) are commonly used, and due to the cylindrical structure of the rotor, it can be assumed that the synchronous inductances in the d and q axes are equal because there is no reluctance difference. This assumption aids in the design of surface-mounted magnet motors. The structure of the motor is both inexpensive and simple because magnets can be easily mounted on the rotor surface. Embedded magnet (EM) motors consist of permanent magnets located within slots (Salminen, 2004).

In PMSM designs, there are two different rotor topologies: internal and external. These have different structures based on the arrangement of magnets. In Figure 2, there are internal rotor SM or EM structures (Dianov et al., 2010). Figure 3 shows external rotor surface or embedded magnet structures. (Yao v et al., 2018).

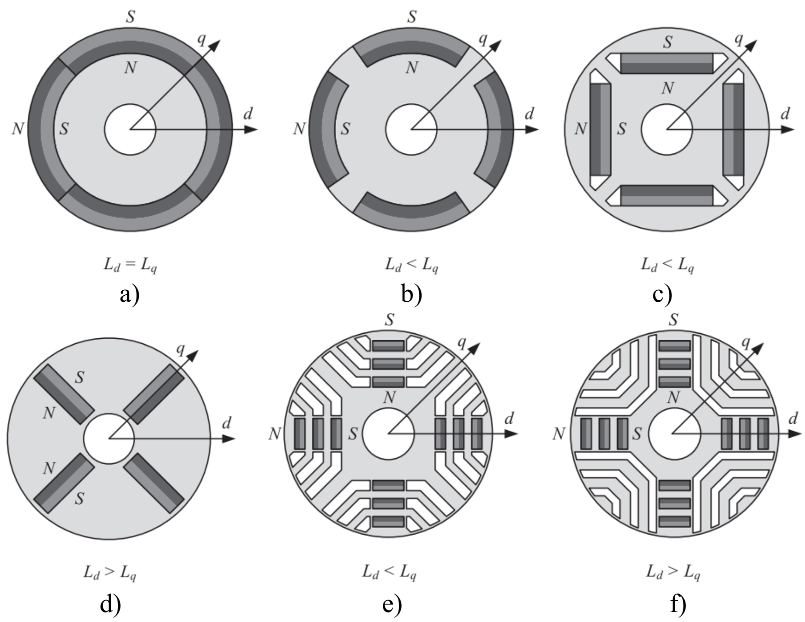


Figure 2. Internal rotor PMSM topologies: a) SM rotor, b) SM embedded rotor, c) EM rotor, d) Embedded radial magnet rotor, e) SM-supported synchronous reluctance, f) SM-supported synchronous reluctance (Dianov et al., 2022)

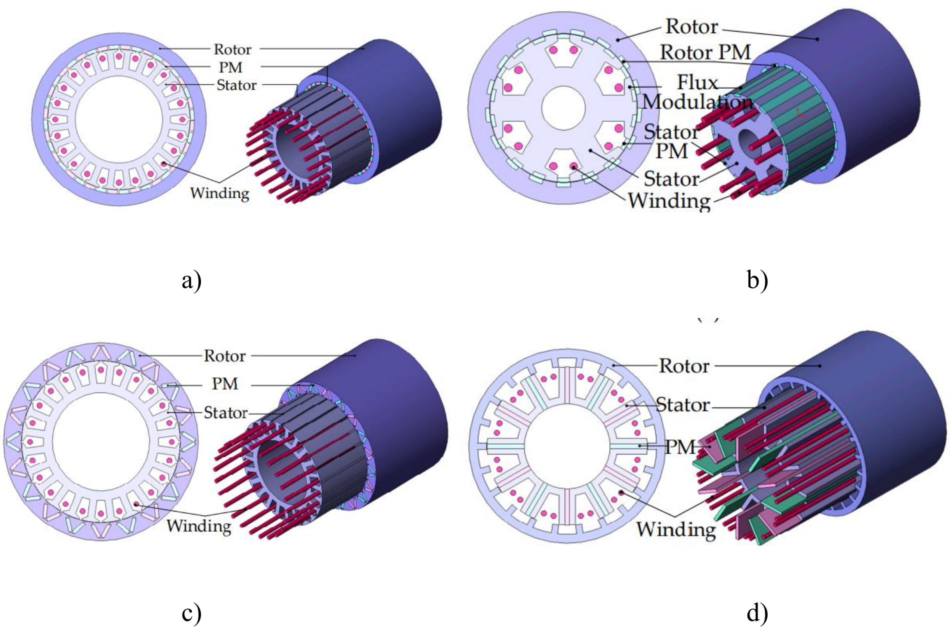


Figure 3. External rotor PMSM topologies: (a) SM rotor, (b) SM embedded rotor, (c) V-type EM rotor, (d) Embedded radial magnet rotor (Yao v et al., 2018)

Permanent Magnets Design

The first industrial artificial alloy magnets were AlNiCo magnets manufactured in the 1930s. Ferrite magnets emerged in the 1960s, followed by the development of Samarium Cobalt (SmCo) magnets in the 1970s. NdFeB magnets, developed in 1984, are the magnets with the highest energy density among industrial magnets (Ünsal, 2022). Classification of commercially used magnets is shown in Figure 4.

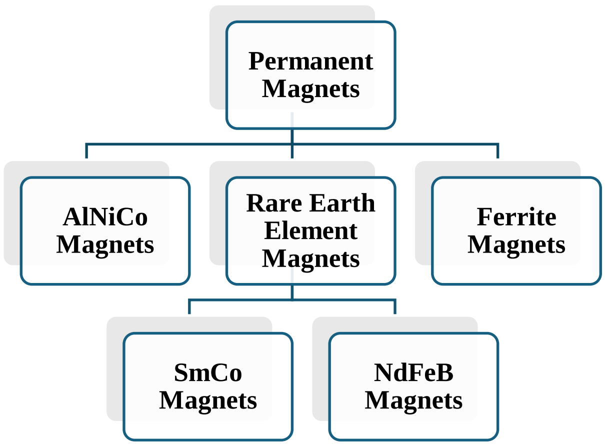


Figure 4. Classification of permanent magnets

Table 2. Properties of commercially used magnets (Eklund and Eriksson, 2019)

Magnet Type	Br [T]	Hci [kA/m]	BHmax [kJ/m3]	Tc [°C]
AlNiCo	0.55-1.37	38-151	10.7-83.6	900
Hard Ferrite	0.2-0.46	140-405	6.4-41.8	450
NdFeB	1.08-1.49	876-2710	220-430	300
SmCo	0.87-1.19	1350-2400	143-251	800

Table 2 presents the characteristics of commercially produced magnets at temperatures ranging from 20°C to

30°C. Parameters such as residual induction (Br), coercive force (Hci), maximum energy product (BHmax), and Curie temperature (Tc) are indicated (Eklund & Eriksson, 2019). When considering four different magnet materials AlNiCo, Ferrite, NdFeB, and SmCo for elevator PMSM traction motors:

AlNiCo: High temperature resistance and mechanical strength are provided, but it has a low energy product. It may be suitable for precision applications, but high performance is expected in elevators.

Ferrite: It is a low-cost option with a low energy product. It can be used in elevator motors, but it may lead to larger and heavier motors, reducing overall efficiency.

NdFeB: It offers a high energy product and excellent magnetic properties, resulting in high torque and efficient motors. Despite price fluctuations and temperature sensitivity, it provides the best performance for elevator traction motors and is widely used.

SmCo: Despite having a lower energy product than NdFeB, it offers high temperature resistance and thermal stability.

It could be a good option for elevator motors operating under high temperature conditions. The best option for PMSM traction motors used in elevators is NdFeB magnets, as they provide high torque and efficiency. However, for motors that need to operate under high temperature conditions, SmCo magnets can also be a suitable choice. AlNiCo and ferrite magnets are less preferred for elevator traction motors due to their lower energy products and suitability for specific applications. However, Yetis conducted a thesis study in 2017 achieving the design of an elevator traction motor with low torque ripple using ferrite magnets (Yetis, 2017).

Elevator Traction Systems with Surface-Mounted (SM) Interior PMSMs

Due to the rotor structures of PMSMs, they can be classified into two groups: surface-mounted and embedded magnet. When we look at the literature and examine elevator traction motors in the current industry, it is observed that SM motors are commonly used. Advantages of SM-PMSM according to elevator systems:

- Higher efficiency: SM motors provide high efficiency even at low speeds, contributing to reduced energy consumption and operating costs.
- Higher torque density: SM-PMSM has higher torque density compared to EM rotor structures. This allows for the use of smaller and lighter motors in elevator systems.
- Simpler cooling: Even at low speeds, SM motors provide more effective cooling. This enables the motor to have higher temperature tolerance and longer lifespan.
- Faster response time: SM motors offer faster dynamic response times. This allows for faster acceleration and deceleration of the elevator, thus increasing passenger comfort.

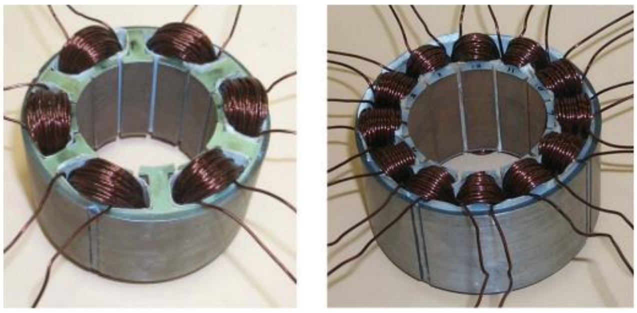
Disadvantages of SM-PMSM according to elevator systems:

- Fragile rotor structures: Placing the magnets on the outer surface of the rotor makes them more susceptible to mechanical damage. While this may cause fewer issues at low speeds, it can raise concerns about long-term reliability and durability.
- Lower maximum speed: Due to centrifugal forces in SM motors, their maximum speeds are lower compared to EM motors.

Windings Design

The number of stator slots, rotor poles, phase number, and winding number are related. Fractional slot/pole combinations are generally preferred to reduce torque ripple (Leu, 1992). In PMSMs, windings can be connected in either delta or star configurations, similar to induction motors (Yan, 2009). Delta connection is preferred for applications requiring low speed and low torque, whereas star connection is used for applications requiring low speed and high torque (Gambhir & Jha, 2013).

PMSMs can be single-phase or multi-phase depending on the application type. Single or multi-layer winding methods are used in windings. Single-layer windings have only one winding per stator slot and are typically used for simpler and less complex applications. While single-layer windings are easier to manufacture and maintain, they generally offer lower efficiency and performance. Double-layer windings have two windings per stator slot and are used to provide higher performance and better magnetic field distribution. Single-layer winding structures have high self-inductance values, limiting short-circuit currents in the motor. Single-layer windings are preferred for constant torque variable speed applications (EL-Refaie, 2010). Figure 5 shows single and double-layer winding structures.



a) b)

Figure 5. Concentrated winding types; a) Single-layer winding b) Double-layer winding (EL-Refaie, 2010)

When selecting slot-pole combinations, the winding type is considered an important constraint factor. A slot-pole combination that allows for the use of concentrated windings is preferred. The main reasons for using concentrated windings over distributed windings are to increase motor efficiency and facilitate production. In motors designed with concentrated windings, the torque per unit volume is high, and the fluctuation of output torque is low. Since the coil end lengths in concentrated windings are shorter than those in distributed windings, the amount of winding placed in the slots decreases. Shortening conductor lengths reduces resistance and copper losses, allowing for increased motor efficiency (Guneri, 2015). Figure 6 depicts single and double-layer, distributed and concentrated winding types.

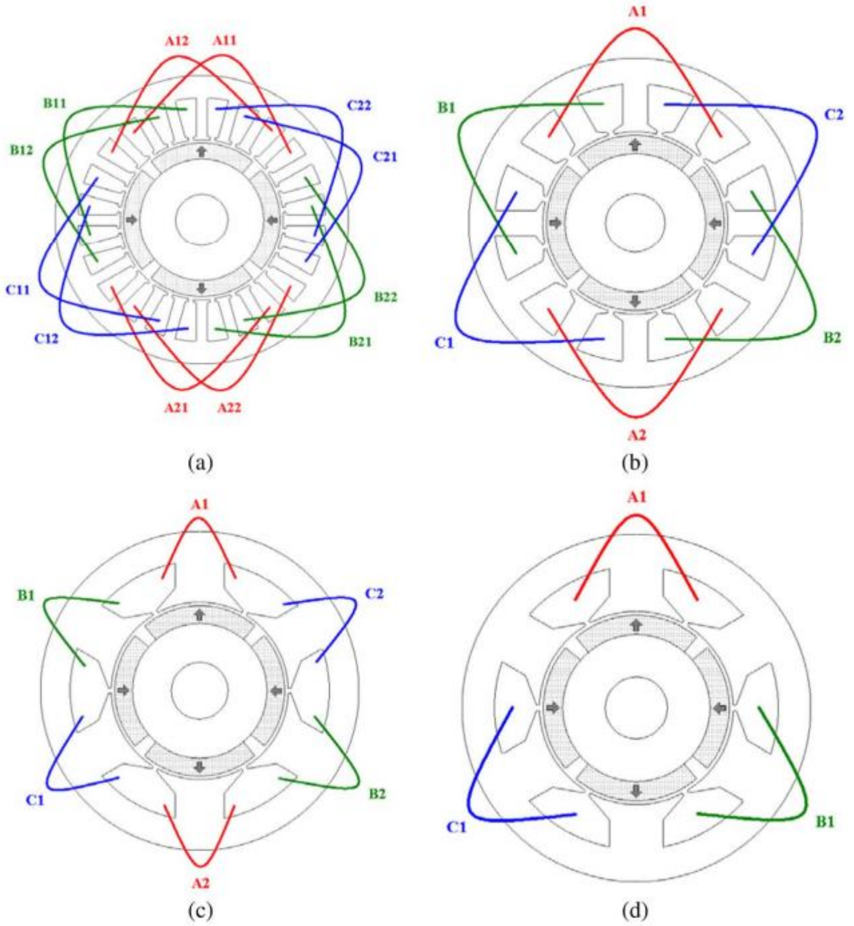


Figure 6. Winding types: a) Distributed double-layer winding b) Distributed single-layer winding c) Concentrated double-layer winding d) Concentrated single-layer winding (EL-Refaie, 2010)

Determining the Slot/Pole Combination

In PMSMs, the slot/pole combination is an important design parameter. This combination refers to the number of stator slots and the number of magnetic poles on the rotor. Choosing the correct slot/pole combination improves the voltage and current waveforms of the motor, reduces harmonics, and enhances the efficiency and performance of the motor.

The slot/pole combination is fundamental in determining the winding factor. A high winding factor is a parameter that directly affects the efficiency and performance of the motor. The correct selection of the slot/pole combination increases the motor's efficiency by reducing iron losses and the impact of high-frequency harmonics. A properly chosen slot/pole combination allows for more compact and lighter designs by reducing the motor's size and weight (Güuneri, 2015; Tanc, 2014; Wang et al., 2008).

When we examined slot-pole combinations, we have found many suitable configurations. To determine the correct configuration, the number of slots per pole per phase (q) must be established. Equation 1 expresses the number of slots per pole per phase. It is expressed in the Equation 1, number of slots N_{slot}, number of poles N_p and number of phases n_f (Tanç, 2014).

$$q = \frac{N_{slot}}{N_p \cdot n_f} \tag{1}$$

If the q value is less than 1, the motor is referred to as a fractional slot winding motor. To achieve optimal flux distribution and torque density, number of slots and poles are kept close together (Avsar et al., 2024; Wang et al., 2008). Table 3 shows the winding factor values for slot/pole combinations based on double-layer winding type.

Table 3. Double-layer slot/pole combinations winding factor (k_w) table (Meier, 2008)

$N_{slot}\backslash N_p$	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38
6	0,866		0,866				0,866		0,866				0,866		0,866			
9		0,866	0,945	0,945	0,866						0,866	0,945	0,945	0,866				
12	q=1		0,866	0,933		0,933	0,866								0,866	0,933		0,933
15				0,866		0,951	0,951		0,866									
18		q=1			0,866	0,902	0,945		0,945	0,902	0,866							
21						0,866	0,87		0,953	0,953		0,89	0,866					
24			q=1				0,866		0,933	0,95		0,95	0,933		0,866	0,76		
27								0,866	0,877	0,915	0,945	0,954	0,954	0,945	0,915	0,877	0,866	
30				q=1					0,866	0,874		0,936	0,951		0,951	0,936		0,874
33										0,866		0,903	0,928		0,954	0,954		0,928
36					q=1						0,866	0,867	0,902	0,933	0,945	0,953		0,953
39		q > 1										0,866	0,863		0,918	0,936		0,954
42						q=1							0,866		0,89	0,913		0,945
45														0,866	0,859	0,886		0,927
48							q=1								0,866	0,857		0,905
51																0,866		0,88
54								q=1									0,866	
57																		0,866
60									q=1									

	Inappropriate combinations of design		k_w < 0.866

Equation 2 represents combinations where the number of slots is two less or two more than the number of poles, resulting in machines with high flux distributions and high torque densities (Soyaslan et al., 2023; J. Wang et al., 2008).

$$N_{slot} = N_p \pm 2 \tag{2}$$

Compared to motors with single-layer winding structures, motors with double-layer winding structures have higher iron losses and longer winding heads. The use of double-layer windings in motors contributes to reducing eddy current losses, torque ripples, and space harmonic components between the EMF (EL-Refaie, 2010).

Cogging Torque and Torque Ripple

Elevator cabin comfort is one of the most crucial parameters during travel. Vibration and noise occurring in the elevator machine greatly affect this comfort. Therefore, minimizing these vibrations and noises in elevator machine design is essential. One of the significant contributors to vibration and noise during cabin travel is cogging torque and torque ripple (Soyaslan et al., 2019). Achieving high-quality and smooth output torque is essential to minimize cogging torque and torque ripple. There are various methods to reduce cogging torque and torque ripple. Through design studies, selecting appropriate slot/pole combinations and optimizing stator and rotor geometry can effectively reduce cogging torque and torque ripple.

Application of skewing is performed during the design stage of the motor. Providing skewing along the axial direction of the stator teeth or rotor magnets reduces the effect of harmonics in the motor's magnetic circuit and decreases torque ripples. The skew angle can be analytically determined in Equation 3-4 (Islam et al., 2009). Here, θ_{skew} refers to the skew angle, N_{period} refers to cogging per period, N_p refers to number of poles and N_{slot} refers to number of slot. The greatest common divisor of N_p and N_{slot} is expressed as $GCD(N_p, N_{slot})$. Figure 3 illustrates the step skew of the magnets on the rotor. Table 4 shows the optimum skew angle according to slot/pole combinations.

$$\theta_{skew} = \frac{360}{N_{slot}N_{period}} \quad (3)$$

$$N_{period} = \frac{Np}{GCD(N_p,N_{slot})} \quad (4)$$

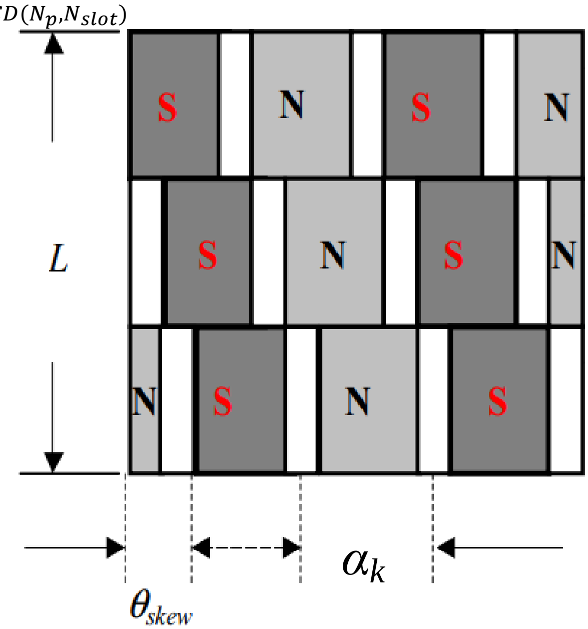


Figure 7. Three-step skew arrangement (Islam et al., 2008)

Table 4. Optimal skew angle according to slot/pole combinations

Number of slot (N_{slot})	12	12	18	18	24	24
Number of pole (N_p)	10	14	16	20	22	26
Cogging period (N_{period})	5	7	8	10	11	13
Optimal skew angle (θ_{skew})	6°	4.28°	0.44°	2°	1.36°	1.15°

Conclusion

Important topics such as the magnetic properties of grain-oriented silicon steel sheets used in stator construction, B-H curves, lamination forming, and stacking factors have been addressed. Two different rotor topologies and magnet arrangements, namely internal and external, have been investigated in PMSM designs. Additionally, the use of four different magnet materials, namely AlNiCo, Ferrite, NdFeB, and SmCo, has been compared for PMSM traction motors in elevators. Single-layer and double-layer winding configurations, distributed and concentrated winding configurations, have been compared. Fractional slot/pole combinations, which directly affect the performance and comfort of PMSMs, have also been examined based on information obtained from the literature. Particularly, structures with high winding factors, such as 12/10, 12/14, 18/16, 18/20, 24/22, and 24/26, have been identified. Finally, studies on skewing to reduce cogging torque and torque ripple have been addressed.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

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