

IMPACT OF SALIENCY RATIO VARIATION ON TORQUE PERFORMANCE IN INTERIOR PERMANENT MAGNET SYNCHRONOUS MOTOR

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DOI: <https://doi.org/10.5281/zenodo.15727876>

Published Date: 24-June-2025

Abstract: This paper studies effects of changes in saliency ratio on the electromagnetic torque performance of Interior Permanent Magnet Synchronous Motors (IPMSMs). The saliency ratio (q-axis to d-axis inductance ratio) L_q/L_d has a decisive impact on the formation of both the magnet and reluctance torque in the IPMSM. A MATLAB dq-axis dynamic equations simulation model was developed to assess the torque response with different saliency ratios. The results reveal that as the saliency ratio increases, the average and peak torque increase on the whole, mainly because the contribution of reluctance torque becomes considerable. A motor produces only magnet torque at the saliency ratio of unity, and the reluctance torque becomes dominant as L_q becomes larger than L_d . It can be seen by the time-waveform of the electromagnetic torque higher torque values obtained by larger saliency ratio. Besides the torque improvement, the simulation showed that the torque ripple increased slightly which means a trade-off between performances and smoothness. Additionally, when analyzing the stator current dynamics it was observed that as the saliency value increases i_q remains rather the same, although i_d is outlined with more dynamics, resulting in profound transients in higher saliency ratios. The simulation also generated characteristic curves of saliency ratio versus average torque, peak torque and torque ripple. These results validate that the saliency ratio greatly affects the performance and dynamic characteristic of IPMSMs. This knowledge can be used to optimize rotor design for high performance electric drive applications. The MATLAB model developed in this work is a flexible platform for design assessment and can also be used for testing control strategies or for validating experimental outcomes.

Keywords: Electromagnetic torque, interior permanent magnet synchronous motor, MATLAB simulation, saliency ratio, stator currents.

I. INTRODUCTION

Permanent Magnet Synchronous Motors (PMSMs) have gained widespread popularity in modern electric drive applications due to their superior efficiency, compact size, and high torque-to-weight ratio. These motors are especially attractive for applications in electric vehicles, industrial automation, and aerospace systems, where performance and reliability are paramount [1 – 4]. Among the various configurations of PMSMs, the Interior Permanent Magnet Synchronous Motors (PMSMs) are widely used in recent electric drives due to their high efficiency, compact size and high torque to weight

ratio. These motors are particularly suitable for many of the applications in electric vehicles, industrial automation, and aerospace systems for high performance and reliability reasons [5, 6] is one of them and is exploited for its unique rotor topology, as depicted in Figure 1. The magnets are buried at the rotor core instead of being mounted on the surface in IPMSM. This internal location leads to geometric saliency which will cause disparate inductances on the d-axis and q-axis. Hence, the IPMSMs enjoy presence of an extra torque component, called reluctance torque, which supplements the torque produced by permanent magnets [7 – 10]. The electromagnetic torque of an IPMSM is the sum of magnet torque and reluctance torque. The force that arises from the reluctance torque component is dependent on the saliency ratio, which is the ratio of the q-axis inductance to the d-axis inductance (L_d/L_q). A larger saliency ratio results in a larger difference of these inductances and therefore reinforces the reluctance torque contribution. This feature gives a possibility of torque optimization without torque increase in the current and magnetic flux [11 – 15]. However, the design compromise in raising saliency ratio is not always obvious. Although a large saliency ratio can produce more torque, torque ripple occurs and control becomes more complex. Thus, it is crucial to provide a comprehensive explanation for the influence of saliency ratio on torque performance in order to support knowledge-based motor design as well as control design [16, 17].

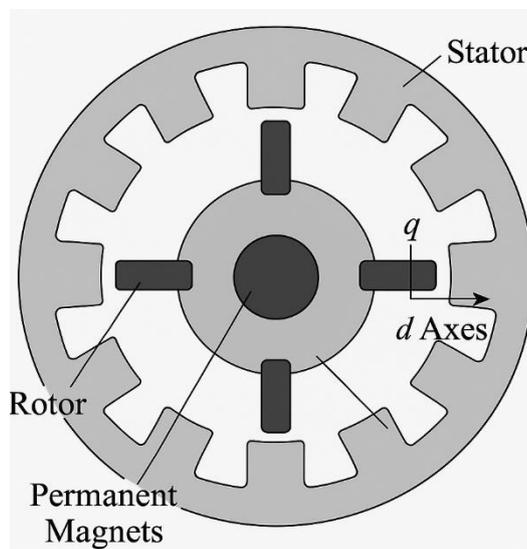


Figure 1: Structure of IPMSM

However, few works are available in literature concerned with the quantitative simulation-based analysis of saliency ratio impact on torque in IPMSMs. This deficit is intended to be filled in this work, by performing a systematic study using a MATLAB dq-axis model. Its purpose is to model the impact of variations in the saliency ratio on different torque variables, such as average torque, peak torque, and torque ripple, thereby offering practical insights for motor designers and control engineers.

II. METHODOLOGY

The transient behaviour of PMSM which is usually modeled by a set of equations written in a rotor reference frame as shown in Equations (1) to (13) [18 – 20].

The d- and q-axis voltage equations are given by:

$$V_q = R_s i_q + \frac{d}{dt}(\lambda_q) + \omega_r \lambda_d \tag{1}$$

$$V_d = R_s i_d + \frac{d}{dt}(\lambda_d) - \omega_r \lambda_q \tag{2}$$

Where the q- and d-axis flux linkages in the rotor reference frame is

$$\lambda_q = L_q i_q \tag{3}$$

$$\lambda_d = L_d i_d + \lambda_m \tag{4}$$

Substituting Equations (3) and (4) in Equations (1) and (2),

$$V_q = R_s i_q + \frac{d}{dt}(L_q i_q) + \omega_r (L_d i_d + \lambda_m) \quad (5)$$

$$V_d = R_s i_d + \frac{d}{dt}(L_d i_d + \lambda_m) - \omega_r (L_q i_q) \quad (6)$$

Resolving further,

$$V_q = (R_s + \frac{d}{dt}L_q)i_q + \omega_r L_d i_d + \omega_r \lambda_m \quad (7)$$

$$V_d = -\omega_r L_q i_q + \left(R_s + \frac{d}{dt}L_d\right) i_d \quad (8)$$

$$\lambda_m = \lambda_{af} = L_m i_{fr} \quad (9)$$

Solving Equations (7) and (8) further gives the following:

$$\frac{di_q}{dt} = -\frac{R_s}{L_q} i_q - \frac{\omega_r L_d}{L_q} i_d + \frac{V_q}{L_q} - \frac{\omega_r \lambda_m}{L_q} \quad (10)$$

$$\frac{di_d}{dt} = \frac{\omega_r L_q}{L_d} i_q - \frac{R_s}{L_d} i_d + \frac{V_d}{L_d} \quad (11)$$

In terms of mechanical rotor speed, the d- and q-axis current can be expressed as

$$\frac{di_q}{dt} = \frac{1}{L_q} V_q - \frac{R_s}{L_q} i_q - \frac{L_d}{L_q} P \omega_{rm} i_d - \frac{\lambda_m P \omega_{rm}}{L_q} \quad (12)$$

$$\frac{di_d}{dt} = \frac{1}{L_d} V_d - \frac{R_s}{L_d} i_d + \frac{L_q}{L_d} P \omega_{rm} i_q \quad (13)$$

The general mechanical equation for the motor is:

$$T_e = T_l + T_d + B \omega_{rm} + J \frac{d}{dt} \omega_{rm} \quad (14)$$

Electromagnetic torque of the motor in terms of d- and q-axis flux linkages, rotor flux linkage, and d- and q-axis inductances as stated in [21 – 24] is given as:

$$T_e = 1.5P(\lambda_d i_q - \lambda_q i_d) = 1.5P[\lambda_m i_q + (L_d - L_q)i_d i_q] \quad (15)$$

where:

$$\frac{d\lambda_m}{dt} = 0$$

V_q and V_d : q- and d-axis voltages

i_q and i_d : q- and d-axis currents

L_q and L_d : q- and d-axis inductances

λ_q and λ_d : q- and d-axis flux linkages

R_s : Stator resistance

ω_r : Electrical rotor speed

ω_{rm} : Mechanical rotor speed

λ_m : Rotor flux linkage

P: Number of poles

B: Viscous frictions coefficient

J: Inertia of the shaft and the load system

T_d: Dry friction torque

T_l: Load torque

T_e: Electromagnetic torque

θ_r: Electrical Rotor angular position

θ_m: Mechanical Rotor angular position

$$\text{The saliency ratio is given as: } \frac{L_q}{L_d} \tag{16}$$

This equation shows that the reluctance torque is dependent on the difference between the d- and q- axis inductances. When the two inductances are the same, there is not reluctance torque, and only the electromagnet torque contributes to the entire output. With the increasing of the saliency ratio, the reluctance torque component becomes more remarkable, especially with the presence of both i_d and i_q [25 – 28].

A MATLAB simulation model utilizing a dynamic dq-axis approach was constructed to study the impact of saliency ratio on the electromagnetic torque of IPMSMs. The dq-axis frame model was selected as it successfully represents the time-varying characteristics of stator currents and the effect of the rotor saliency on the electromagnetic torque.

The simulations were carried out based on a typical machine parameter as given in Table 1.

Table 1: Motor parameters for Interior Permanent Magnet Synchronous Motor (IPMSM) Motor

Parameter	Value
Rated power, P	2 kW
Rated voltage, V	240 V
Rated speed, ω	1500 rpm
d-axis inductance, L _d	0.015 H
q-axis inductance, L _q	0.015 H to 0.060 H in steps of 0.01 H
Rotor flux linkage, λ _{af}	10.18 Wb
Number of poles, P	4
Stator resistance, R _s	1.2 Ω
Stator core resistance, R _c	18 Ω
Inertia coefficient, J	0.00021 kg/m ²
Load torque, T _l	12 Nm
Dry friction, T _d	0 Nm
Frequency, f	50 Hz
Viscous friction coefficient, B	0.015 Nms

The fourth-order Runge-Kutta method was utilized to solve the coupled d- and q-axis current differential equations to simulate the time-domain behavior. These equations were obtained from the voltage balance in the synchronous reference frame with the assumption of constant V_d and V_q. A simulation time of 0.5 s was used to obtain transient and steady-state behavior of the motor.

Different L_q was employed for each simulation, with L_d fixed. This permitted systematic changes in the saliency ratio (L_q/L_d), which made it easy to appreciate the effect of the ratio on the torque characteristic. The standard torque expression of IPMSMs was employed in the model to calculate the electromagnetic torque at each step.

Post-processing of the simulation results were used to obtain the average torque, peak torque and torque ripple values for each saliency ratio. These numbers quantitatively afforded a measure to evaluate the role of saliency in the behavior of a motor’s torque. The data were plotted to clarify the trend and to demonstrate the trade-offs among different saliency ratios. This approach provided a comprehensive, repeatable framework for evaluation which could be used to guide motor design decisions.

III. RESULTS AND DISCUSSION

Comparison results indicate that there is a good relationship between the saliency ratio and the electromagnetic torque performance of IPMSMs obtained through simulations. When the q-axis inductance (L_q) was from 0.015 H to 0.060 H (L_d was 0.015 H), the average and the peak torque were improved considerably. This improvement was due largely to the increase in the reluctance torque term at more negative values of $(L_d - L_q)$.

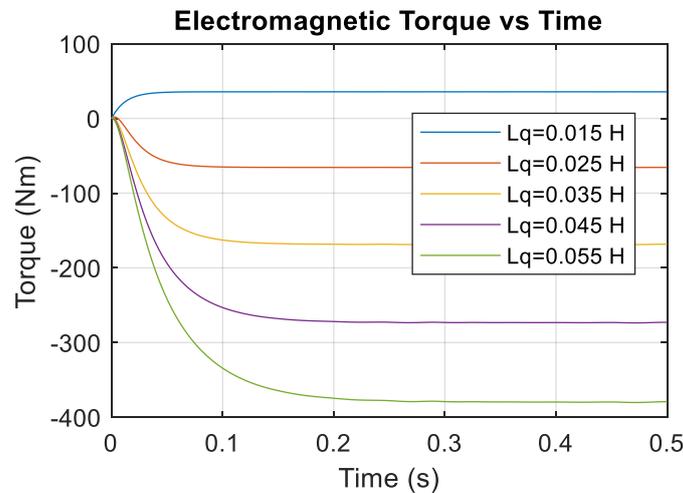


Figure 2: Electromagnetic torque versus time for varying saliency ratios

Figure 2 presents the electromagnetic torque waveform over time for different saliency ratios. A progressive increase in torque magnitude is observed with higher L_q values. The waveforms show both transient and steady state behaviours, providing insight into the stability and dynamic performance of the motor.

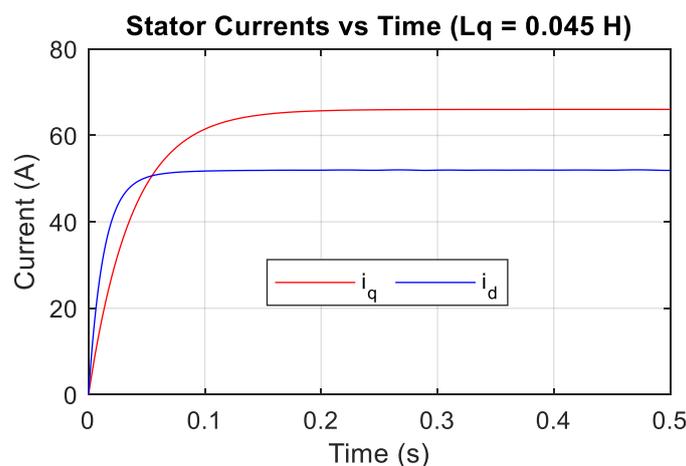


Figure 3: q-axis and d-axis stator currents (i_q and i_d) for saliency ratio $L_q = 0.045$ H

Figure 3 shows the stator currents i_q and i_d for a representative L_q value of 0.045 H. The i_q current, which is primarily responsible for generating magnet torque, demonstrates a relatively stable trend, while i_d , which is more strongly linked to reluctance torque, shows transient oscillations. These oscillations become more prominent at higher saliency ratios, which contributes to torque ripple.

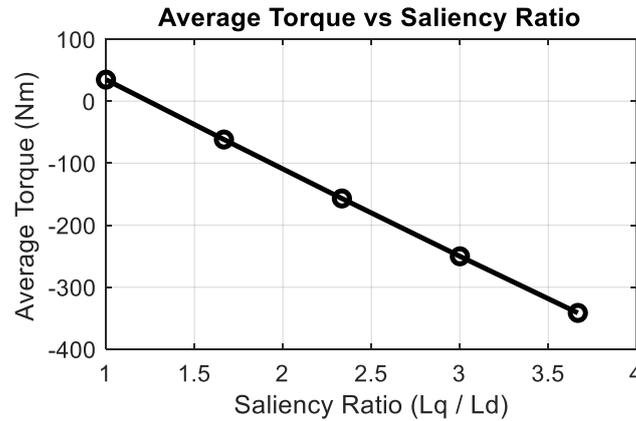


Figure 4: Average electromagnetic torque as a function of saliency ratio

Figure 4 illustrates the relationship between the average torque and saliency ratio. It confirms a monotonic increase in average torque as L_q rises. At unity saliency ratio, where L_q equals L_d , the reluctance torque contribution is zero, and the motor operates purely on magnet torque. As the saliency ratio increases, the reluctance torque adds significantly to the overall torque.

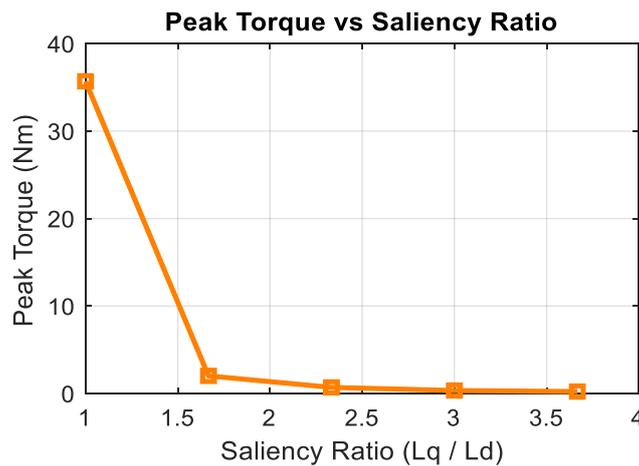


Figure 5: Peak torque versus saliency ratio

Figure 5 captures the peak torque variation with saliency ratio. Similar to average torque, the peak torque exhibits a rising trend with increasing L_q , indicating improved transient torque capability. This is particularly advantageous in applications that demand rapid acceleration or dynamic load response.

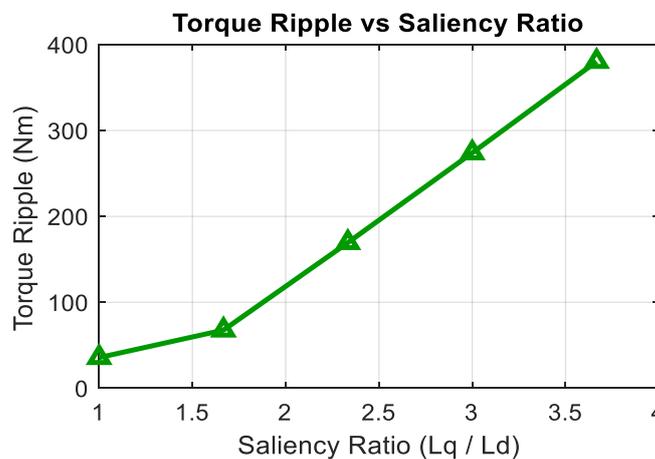


Figure 6: Torque ripple versus saliency ratio

Figure 6 focuses on torque ripple, calculated as the difference between maximum and minimum torque values during the simulation period. As saliency ratio increases, torque ripple also grows slightly. While this increase remains within acceptable limits for most applications, it suggests a tradeoff between higher torque output and the smoothness of operation.

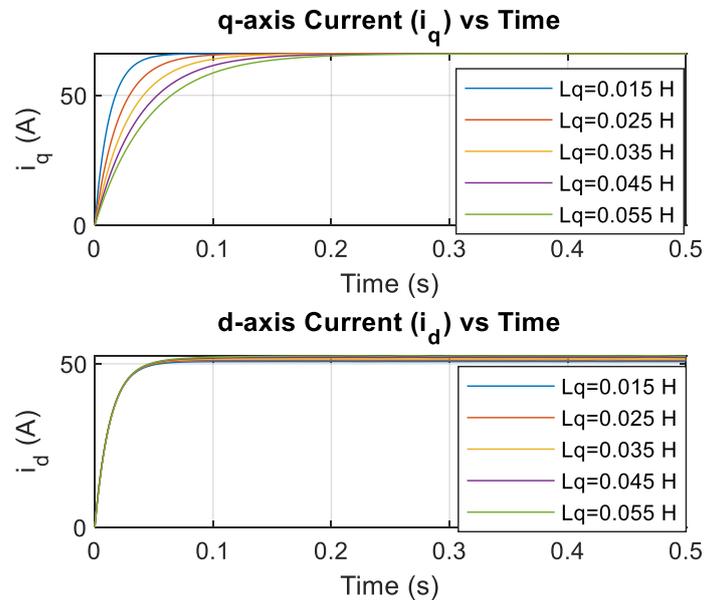


Figure 7: Time-domain profiles of i_q and i_d for multiple saliency ratios

Stator currents i_q and i_d fluctuate wildly over time for various saliency ratios considered in the analysis as shown in Figure 7. L_q increases and dynamic behaviour of both currents becomes more pronounced indicating stronger coupling and significant nonlinearities in system pretty rapidly. Robust control strategies are crucial when employing IPMSMs with extremely high saliency ratios under various operating conditions effectively.

In summary, at unity saliency ratio where L_q equals L_d only magnet torque is present but reluctance torque becomes significant with increasing L_q raising average torque substantially and peak torque moderately. Moderate saliency ratio increases are beneficial for enhancing torque. Very high saliency ratios may introduce significant control challenges due to excessive torque ripple and severe current oscillations. Simulation findings align fairly well with theoretical expectations confirming saliency ratio's pivotal role in bolstering IPMSM performance remarkably well. They provide crucial insights for designers seeking balance between torque output and operational smoothness with overall stability in various applications.

IV. CONCLUSION

The work presented here shows that the saliency ratio plays a key role in fine-tuning the torque output of interior permanent magnet synchronous motors. When the ratio rises, reluctance torque steps in more forcefully, lifting both the average and peak torque levels. That boost makes IPMSMs with high saliency ratios sought after in areas needing tight torque packs, from electric cars to fast industrial drives. Yet the same feature can also stir up extra torque ripple and quick swings in current that designers must face. Careful control strategies-such as online filtering and adaptive current shaping-are needed to tame those rough edges and keep the machine calm. The findings highlight a sweet spot where saliency ratio lifts torque without letting stability slip away. To explore that spot, the team built a MATLAB simulation toolbox that quickly shows how different design choices affect motor behaviour under real-world loads. By swapping material constants, stator slot angles, or rotor geometry, users can spot trade-offs without waiting for costly physical prototypes. The model is set up to plug in advanced methods such as vector control or direct-torque control, letting engineers gauge their value in the same virtual testbed.

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