Novel Design of Flux-Intensifying Interior Permanent Magnet Synchronous Machine

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Abstract :

This paper proposes a new rotor design for flux-intensifying interior permanent magnet synchronous machine (FI-IPM SM) which has similar torque-speed and power capabilities to a traditional flux-weakening IPM SM (FW-IPM SM). Design steps for the rotor structure of the new machine are laid out and discussed to emphasize key designing challenges. The proposed FI-IPM SM and a FW-IPM SM with similar torque-speed capability, are made to evaluate performances in power conversion as well as self-sensing capability at very low speed. Finite-element analysis (FEA) is used to evaluate the machine performances. The proposed FI-IPM SM shows less variation in the saliency when the machine is loaded, leading to a possibility of better self-sensing performance at very low speed as compared to the traditional FW-IPM SM. Experimental results on the self-sensing performance of these two machines are also shown for verification.

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Novel Design of Flux-Intensifying Interior Permanent Magnet Synchronous Machine

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Outline

1. Introduction
2. Rotor design
3. Power conversion capability
4. Self-sensing capability at very low speed
5. Conclusions

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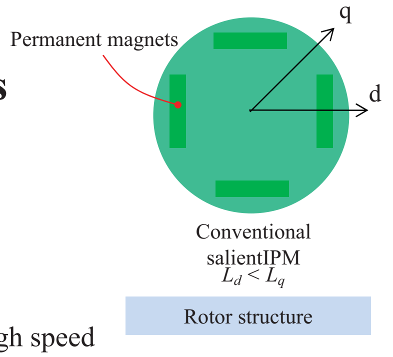
1. Introduction

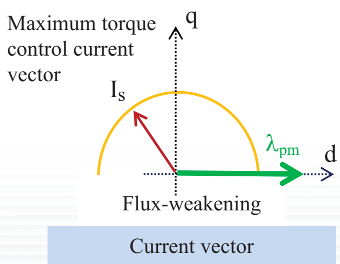
Conventional salient IPM machines



Advantage

- High output density, high efficiency
- $L_d < L_q$ due to thick mangnets
- Generate both Magnet torque and reluctance torque
- Capable of flux-weakening control to allow running at high speed

Drawbacks



- Excessive copper loss from flux-weakening current
- Demagnetization of magnets when weakening flux
- High cost of magnets to avoid the above demagnetization
- Degradation of saliency with load current, making sensorless control difficult at very low speeds

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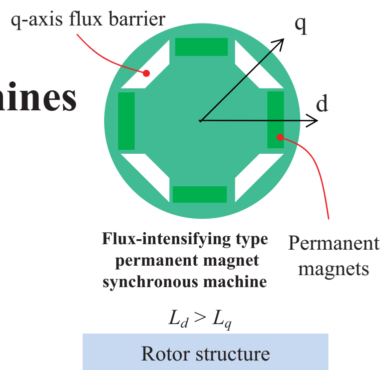
1. Introduction

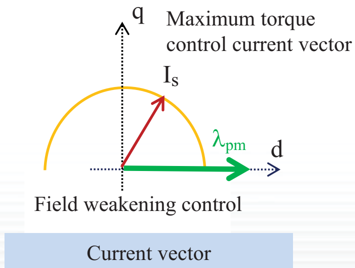
Possibilities of positive salient IPM machines



Characteristics

- $L_d < L_q$ due to flux barriers in q-axis
- Reluctance torque is produced by the positive d-axis current
- Small-to zero flux-weakening current at high speed

Advantages



- Improved torque capability above rated speeds
- Iron loss caused by flux-weakening can be reduced
- Thin magnet is possible with less concern for demagnetization
- Reduced saturation effect from load current
- More suitable for saliency-tracking with carrier signal injection method.

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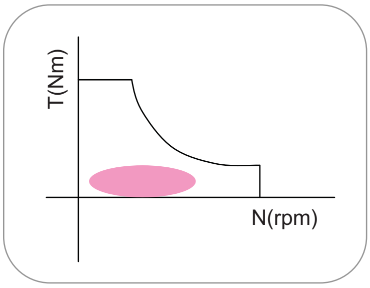
1. Introduction

The issues of traction motors for EV

- ✓ Expand driving range ⇨ Improve efficiency in practical domain
- ✓ Cost reduction ⇨ Reduce the volume of costly material



Need new motor unilizing less amout of magnets

Motor concept	Torque
FW, negative saliency motor $i_d < 0, L_d < L_q$ more magnet with feild weaking	$T = P_n \cdot \{(\phi_a + L_d \cdot i_d) \cdot i_q - L_q \cdot i_d \cdot i_q\}$ Negative Positive
FI, positive saliency motor $i_d > 0, L_d > L_q$ Less magnet with field intensifying	$T = P_n \cdot \{(\phi_a + L_d \cdot i_d) \cdot i_q - L_q \cdot i_d \cdot i_q\}$ Positive Negative

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1. Introduction

Sensorless control at very low speeds

Sensorless control using high frequency signals

- High frequency signal injection
- Interaction between the high-frequency signal and machine saliency
- Not rely on back-EMF voltage
- Suitable at very low speed, including zero speed

Challenges

- Cross-saturationcauses saliency angular offset, leading to estimated position error, at high load conditions
- Insufficient saliency at high load condition due to saturation effect
- Secondary saliencies cause harmonic distortion in the tracked component

A design method for a new type of motor structure is necessary to satisfy performance requirements such as the speed- torque characteristics to resolve the above problems.

⇒ Focus on the magnetic characteristics of flux-intensifying interior permanent magnet synchronous machines

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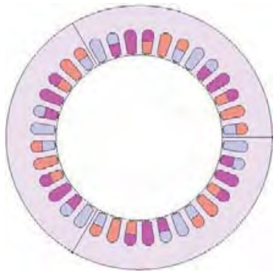
1. Introduction

Testing overview for this presentation

36 slots
Distributed double-layer winding
Rated phase voltage V_s = 109.6 V_{rms}
Rated phase current I_s = 21 A_{rms}



Stator structure

Design parameters

- Focus here only on the rotor design
- The same physical demensions are used for the stator configration to compare with a conventional IPM machine.

Evaluation

What :

- Compare the N-T characteristics and efficiency map
- Compare the sensorless control capability with high-frequency signal injection method

How :

- Simulation with finite-element analysis (FEA)
- Experimental verification of sensorless capabilities

	Rotor	Stator
D_{in} [mm]	25	55
D_{out} [mm]	54	88
Axial length [mm]	100	

Motor size

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2. Rotor design

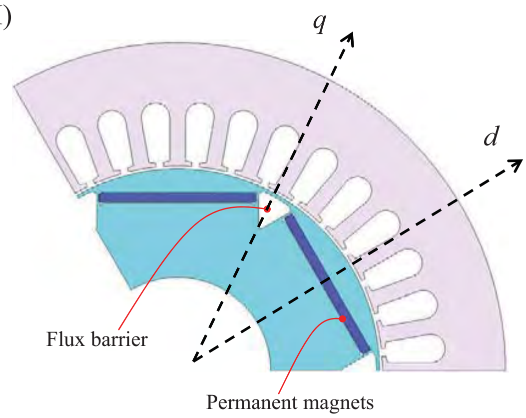
Evaluation based motor structure

Structural characteristics

- Based on conventional IPM machines
- Inset arranged 6pole neodymium magnets (N36SH)
- Specify magnet thickness considering demagnetization
- Small flulx-barrier to prevent magnet flux leakage in the rotor

Summary of Machine data

	Rotor	Stator
Pole or Slot	6pole	36Slot
Magnet	Shin-Etsu: N36H	-
Magnetic steel	Nippon Steel: 50H100	Nippon Stel: 50H600



Base motor structure

Performance characteristics

- d- axis inductance is small because of the thick magnet on the d-axis
- High magnet torque due to large volume of permanet magnet

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2. Rotor design

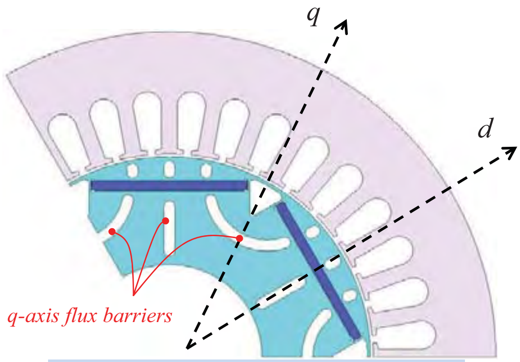
Positive salient motor structure

Initial structure

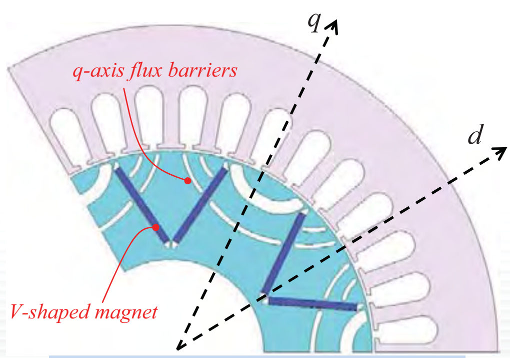
- Same magnets to maintain similar torque production
- Additon of flux barriers arranged on the q-axis
- Multiple layers of flux barriers to significantly reduce L_q
- Greater concern for mechanical stress due to complex geometry

Proposed structure

- V shaped magnet with steel bridge supported in the center
- Slightly thinner and wider mangets
- Multiple layers of q-axis flux barriers



Initial structure



Proposed structure

Magnet size

Machine	Thickness [mm]	Width [mm]	Total Volume [cm³]
FW-IPM	2.5	42	63
FI-IPM	1.8	2 @ 23.85	51.52

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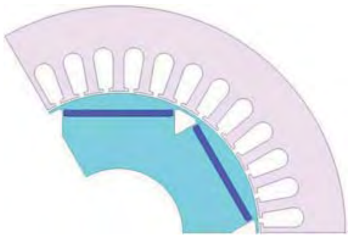
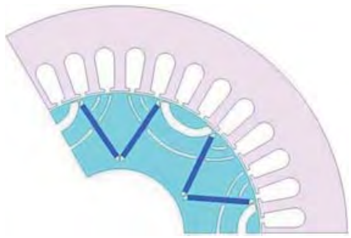
2. Rotor design

Parameter comparison between base motor and proposed motor

	Base motor (negative saliency)	Proposed motor (positive saliency)
		
λ_{PM}	200.59 mWb	188.57 mWb ↓ ≈ 6 %
λ_{PM} / magnet volume	3.18 mWb/cm3	3.66 mWb/cm3 ↑ ≈ 15 %
L_q	3.61 mH	→ Reduction in L_q 2.33 mH
L_{d+}	N/A	2.17 mH
L_{d-}	2.33 mH	→ Increase in L_d 3.09 mH

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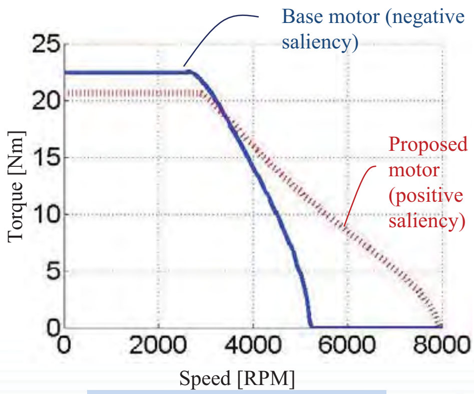
3. Power conversion capability

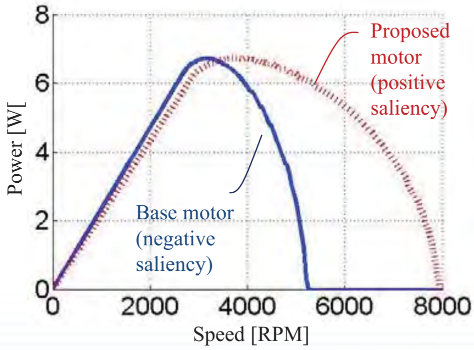
Comparing speed-torque & speed-output characteristics（FEA results）

Proposed motor characteristics

- Slightly lower torque production below rated speed due to lower λ_{PM}
- Superior torque production at higher speed
- Extended speed range



Torque-speed characteristics



Output-speed characteristics

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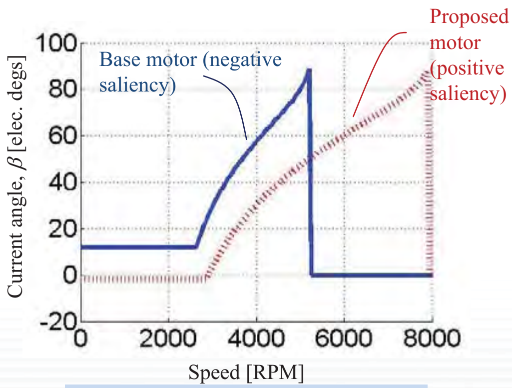
3. Power conversion capability

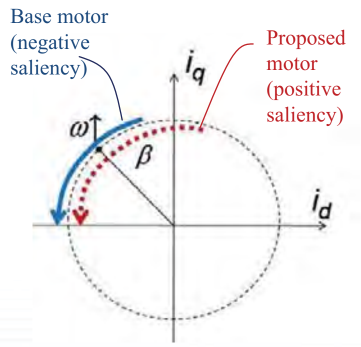
Comparing current control（FEA results）

Proposed motor characteristics

- Positive *Id*(flux-intensifying) current to produce reluctance torque
- Reduced flux-intensifying current at high speed to maintain voltage
- Smaller flux-weakening current than in the FW-IPM for any operating speed
- Demagnetization is of less concern



Control current phase β -speed



Control current drive trajectory

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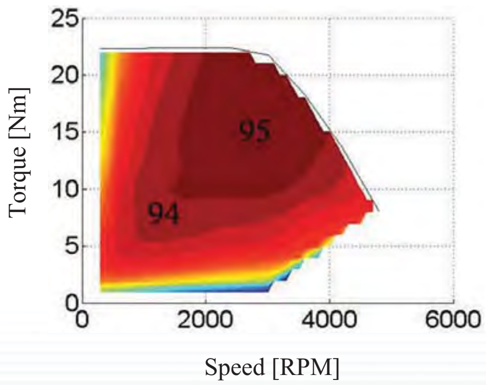
3. Power conversion capability

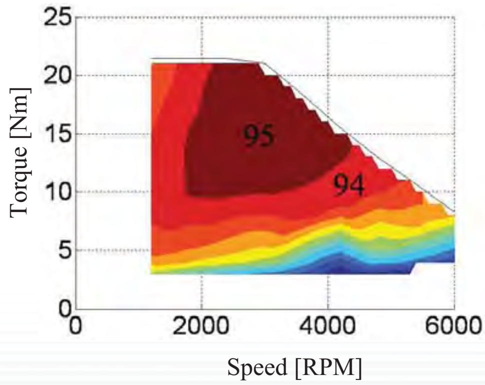
Comparing efficiency map （FEAresults, current limit control：MTPA）

Proposed motor characteristics

- The proposed motor shows similar efficiency profile with extended speed range
- Improved efficiency in the high speed region slightly worsens the low sped load.



Base motor (negative saliency)



Proposed motor (positive saliency)

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4. Self-sensing capability at very low speed

Machine model for high-frequency components

- Complex vector forms in a stationary reference frame

Average inductance $\Sigma L = \frac{L_q + L_d}{2}$ *Differential inductance* $\Delta L = \frac{L_q - L_d}{2}$

$$v_{dq}^{s} = R_s \cdot i_{dq}^{s} + p \cdot \left\{ \Sigma L \cdot i_{dq}^{s} - \Delta L \cdot e^{j2\theta_r} \cdot i_{dq}^{s*} \right\}$$

Carrier voltage $$v_{dqc}^{s} = V_c \cdot e^{j\omega_c t}$$

Induced current $$i_{dqc}^{s} = I_{cp} \cdot e^{j\left(\omega_c t - \pi/2 + \phi_{cp}\right)} + \underbrace{I_{cn} \cdot e^{j\left(-\omega_c t + 2\theta_r + \pi/2 + \phi_{cn}\right)}}_{\text{Negative sequence}}$$

Saliency position ($2\theta_r$), *Saliency offset* (ϕ_{cn})

$$I_{cp} = \frac{V_c}{\omega_c} \frac{\Sigma L}{\Sigma L^2 - \Delta L^2} \qquad I_{cn} = \frac{V_c}{\omega_c} \frac{\Delta L}{\Sigma L^2 - \Delta L^2}$$

Characteristics

- Negative sequence of the induced current contains saliency position (magnet position)
- Magnitude of this component depends on differential high-frequency inductance (saliency)
- Saliency angular offset caused by multiple effects including cross-saturation can lead to estimation errors

⇒**Reliable self-sensing control needs sufficient saliency with small anglular offset**

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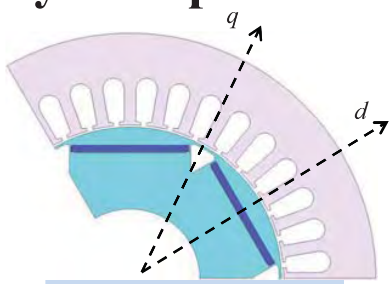
4. Self-sensing capability at very low speed

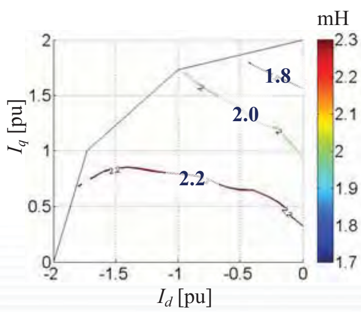
Inductances evaluation (base motor)

- Inductances are sensitive to I_q because of large L_q and saturation effect
- L_q decreases rapidly as loading I_q current increases
- Small cross-saturation in L_d due to I_q current

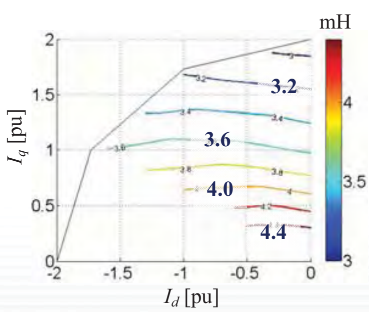


Baseline FW-IPM design

** 0.2 mH increment per line*



L_d [mH]



L_q [mH]

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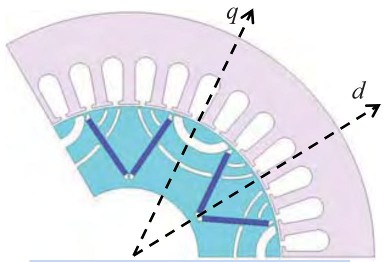
4. Self-sensing capability at very low speed

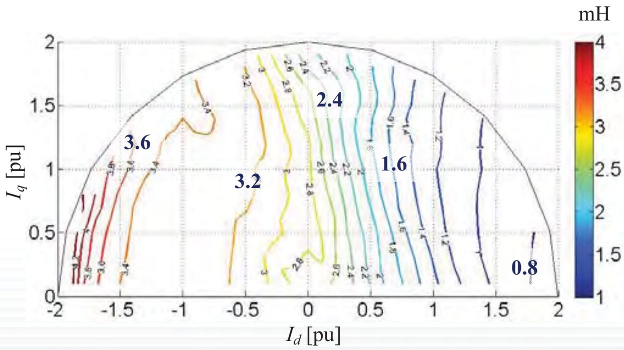
Inductance evaluation (proposed motor)

- Inductances are sensitive to I_d because L_d is larger than L_q
- Saturation in L_d caused by I_d is significant
- L_q is much less sensitive to loading current

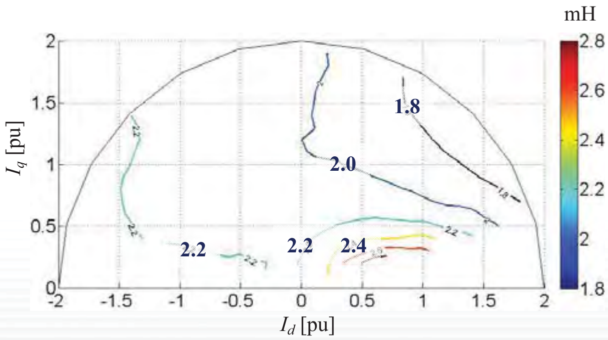


Proposed FI-IPM design

* 0.2 mH increment per line



L_d [mH]



L_q [mH]

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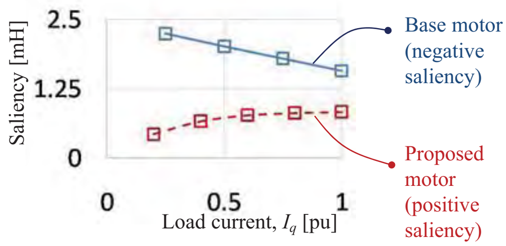
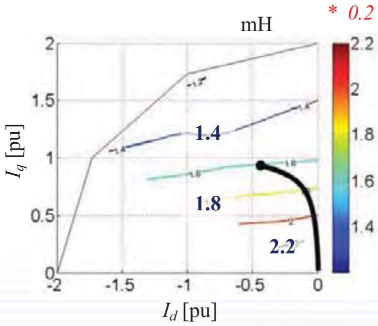
4. Self-sensing capability at very low speed

Effects of magnetic saturation on saliency

- The saliency decreases as the load current I_q increases in the base motor, but the saliency does not decrease in the proposed motor
- In the proposed motor, because the magnets are arranged on the d-axis, the saliency is small and the β angle is also relatively small at maximum torque（MTPA control）

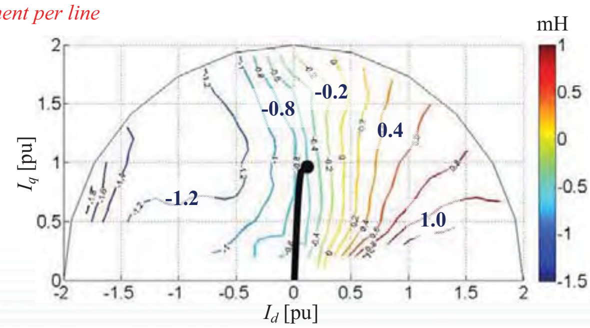


* 0.2 mH increment per line



$L_q - L_d$ [mH] contour

Base motor (negative saliency)



$L_q - L_d$ [mH] contour

Proposed motor (positive saliency)

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4. Self-sensing capability at very low speed

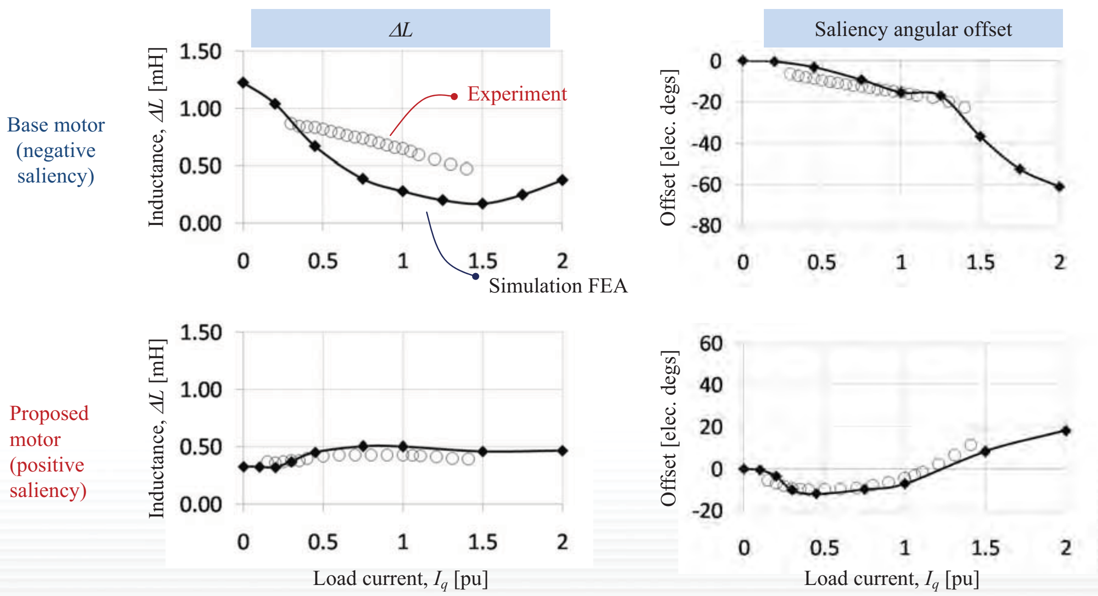
Summary of inductance evaluation

	L_q-L_d	L_q	$L_{d\text{-}}$	as loading I_q current increases		
				L_d	L_q	Saliency
Base motor (FW-IPM)	+	large 3.6mH	small 2.3mH	→	↘	↘
Proposed motor (FI-IPM)	-	small 2.3mH	large 3.1mH	→	→	↗

4. Self-sensing capability at very low speed

Self-sensing performance evaluation

•The proposed motor maintains the saliency, nearly independent of load.
•Angular offset in the proposed motor has smaller variation over the full load range

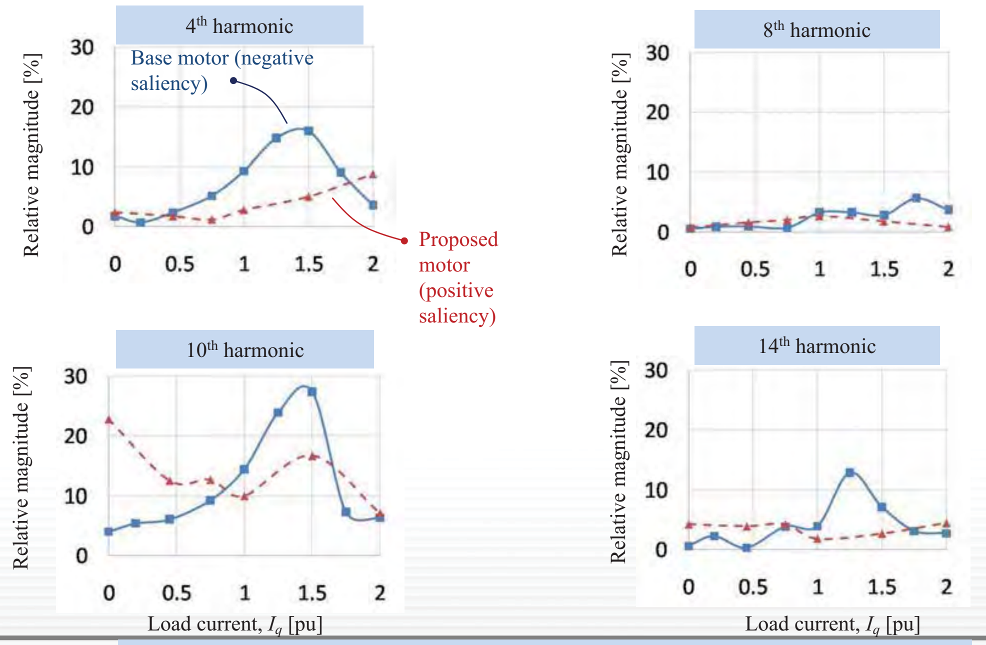


Differential inductance and saliency angular offset as a function of load current

4. Self-sensing capability at very low speed

Harmonic components of local inductance

- Magnitudes of secondary saliency harmonics are relatively lower in the proposed motor



Secondary saliency harmonics as a function of load current

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4. Self-sensing capability at very low speed

Summary of self-sensing capability

	L_q-L_d	L_q	$L_{d\text{-}}$	as loading I_q current increases		
				Saliency	Angular offset	Harmonics
Base motor (FW-IPM)	+	large 3.6mH	small 2.3mH	↘	large	large
Proposed motor (FI-IPM)	-	small 2.3mH	large 3.1mH	↗	small	small

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5. Conclusion

1. A flux intensifying interior permanent magnet synchronous machine that has the same N-T characteristics as an IPM machine was proposed.

- The torque density was largely improved and a maximum toque equivalent to conventional IPM machines was achieved.
- Advantageous for improving power in middle and high speed regions
- Efficiency equivalent to conventional IPM machines was also obtained.
- The volume of magnets can be reduced by limiting flux-weakening current.

2. The self-sensing control capability at low speeds can be improved using the proposed motor.

- The inductance variations caused by load current is small
- The saliency is not affected by large load currents.
- The error in the estimated angle can be largely reduced when loaded heavily
- The harmonic components of the local inductance is relatively small

3. Future work: develop the motor which can reduce the amout of magnet

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