Sensorless Capability of Fractional–Slot Surface–Mounted PM Motors

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Outline

Rotor estimation purpose

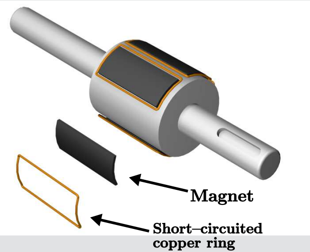
Estimating the rotor position

- The motor have to exhibit a different value of direct and quadrature inductances
- Cross–saturation produces an angular error in the rotor position detection
- SPM machine does not allow the identification of the rotor position (isotropic rotor)
  $\Rightarrow$ Insertion of short circuited ring around each pole. This configuration is called ringed–pole SPM motor.

The ringed–pole SPM motor

Scheme and photo of the ringed–pole rotor configuration

Ringed–pole SPM motor



- Different electromagnetic behaviour along the d– and q–axis at high frequency thanks to the presence of the rotor rings.

Aim of the work

- The ringed–pole solution has been tested with a distributed coil winding
- The possibility to use this configuration with a concentrated coil stator windings is investigated in this paper

Two kinds of motors are investigated:

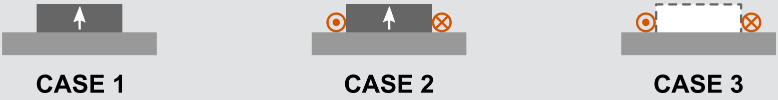
1. distributed coil windings (number of slots per pole per phase $q = 1.5$)
2. concentrated coil windings ($q = 0.5$)

The effect of the conductive ring around each pole is investigated in the frequency domain by means of Finite Elements simulations

FEM analysis

In the following FEM analysis three cases have been analyzed:

- **case 1** only PMs effect is considered, i.e. without the ring.
- **case 2** effect of both the ring and magnets
- **case 3** only the effect of the ring



FEM analysis

Main simulation data

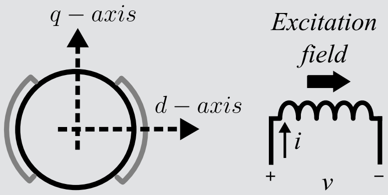
Material	Conductivity (MS/m)
Permanent Magnet	0.69
Iron	0
Copper ring	40

To derive the sensorless capability

- A sinusoidal current at different frequency is imposed in the stator winding (from 10 Hz to 8 kHz)
- The rotor is placed into two different position with respect the stator field

High frequency impedance measurement scheme

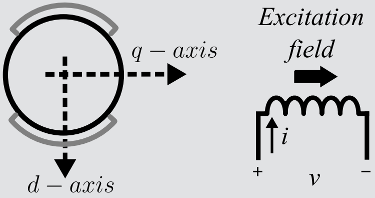
Only *d*–axis current supplied



- The magnetic field is along the *d*–axis and then the *d*–axis impedance can be computed.

High frequency impedance measurement scheme

Only *q*–axis current supplied



- The magnetic field is along the *q*–axis and then the *q*–axis impedance can be computed

High frequency saliency

Referring to an equivalent circuit

Because of the short circuited rings, a saliency dependently on the frequency can be defined as:

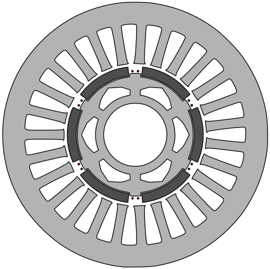
$$\xi(\omega_h) = \frac{\dot{Z}_q}{\dot{Z}_d} = \frac{R_r + j\omega_h L_r}{R_r + j\omega_h L_{rt}}$$

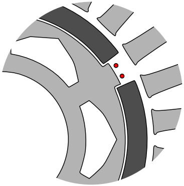
From FE simulations

$$\xi(\omega_h) = \frac{\lambda_q(\omega_h)}{\lambda_d(\omega_h)}$$

Distributed coil winding

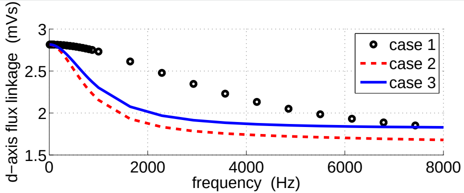
27–**slot** 6–**pole motor (distributed coil windings)**





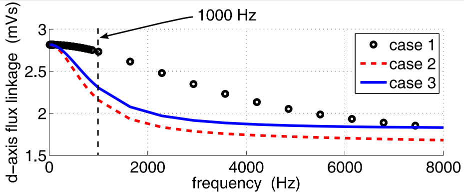
Such configuration corresponds to the motor prototype available in laboratory.

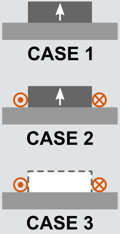
d–axis flux versus frequency (distributed coil windings)



1. The effect of presence of the ring can be noted comparing **case 1** with **case 2** ⇒ *d*–axis flux linkage decreases as the frequency increases
2. The presence of PMs (**case 2**) yields a further reduction on the *d*–axis flux linkage

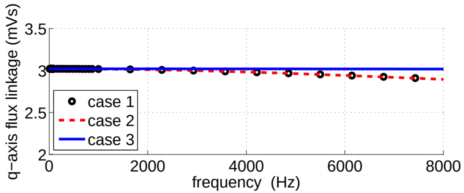
d–axis flux versus frequency (distributed coil windings)

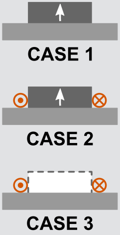




1. The effect of presence of the ring can be noted comparing **case 1** with **case 2** ⇒ *d*–axis flux linkage decreases as the frequency increases
2. The presence of PMs (**case 2**) yields a further reduction on the *d*–axis flux linkage

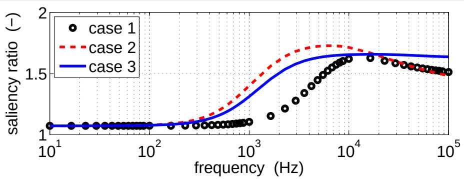
q–axis flux versus frequency (distributed coil windings)





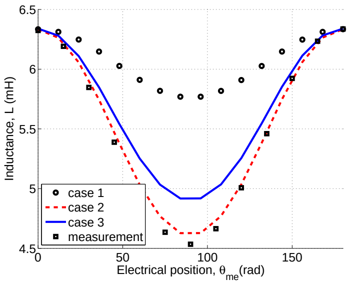
1. The effect of presence of the ring is not appreciable ⇒ the ring has no effect on the *q*–axis flux linkage.
2. The PMs presence yields a slight effect on the *q*–axis flux linkage (**case 1** and **case 2**).

Saliency versus frequency (distributed coil windings)



1. At low frequencies there is a small saliency of about 1.07 due to a slight rotor anisotropy.
2. At 1 *kHz* the saliency increases from 1.1 (**case 1**) to 1.3 (**case 3**) thanks to the rings.
3. Considering the PMs the saliency increases to 1.4.
4. Without rings, almost no saliency variation at 1 *kHz*.

Inductance versus rotor electrical angle at 1 *kHz* (distributed coil windings)

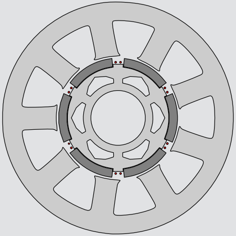


1. The anisotropy is significant only if a ring is present around the pole (**case 2** and **3**).
2. The effect of the PMs conductivity is beneficial to improve the saliency (**case 3** against **case 2**).
3. Experimental tests (squared marker) confirm the accuracy of the motor model.

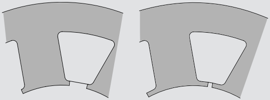
Concentrated coil winding

9–slot 6–pole motor (concentrated coil winding)

Motor sketch



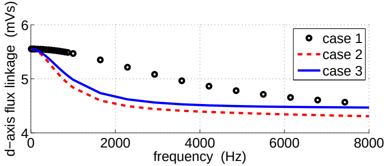
Slot–opening

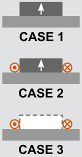


- Effect of the slot opening

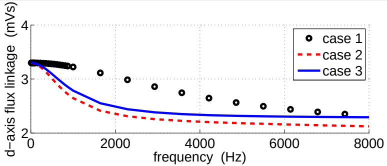
Flux linkage versus frequency (concentrated coil winding)

d–axis – narrow slot opening



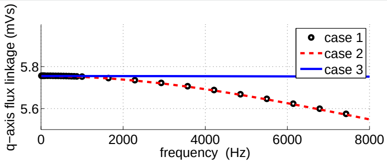


d–axis – wide slot opening

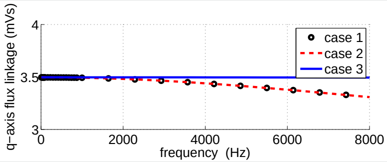


Flux linkage versus frequency (concentrated coil winding)

q–axis – narrow slot opening

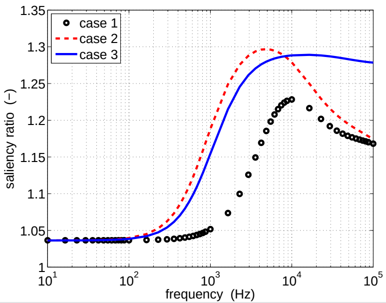


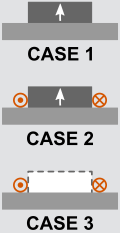
q–axis – wide slot opening



Saliency versus frequency (concentrated coil winding)

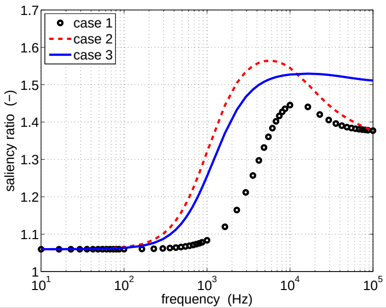
Narrow slot opening

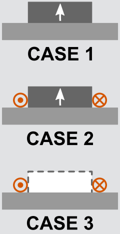




Saliency versus frequency (concentrated coil winding)

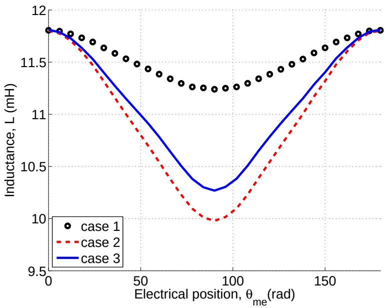
Wide slot opening

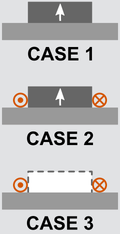




Inductance versus rotor angle (concentrated coil winding)

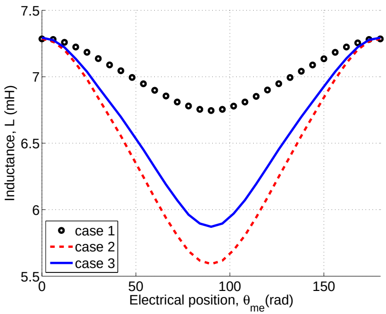
Inductance – narrow slot opening





Inductance versus rotor angle (concentrated coil winding)

Inductance – wide slot opening



Wide versus narrow slot opening

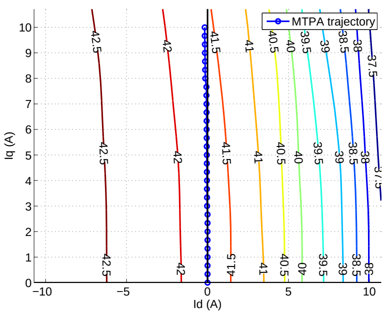
- The results obtained with both the configurations are comparable with those of the 27–6 motor configuration.
- With the narrow slot opening the flux linkages and the inductance values increase respect to the wide slot opening case.
- The saliency with the wide slot opening is greater than that with the narrow slot opening
- In both the cases the sensorless capability with injection of high frequency signals remains still working.

Effect of the iron saturation

Effect of the iron saturation

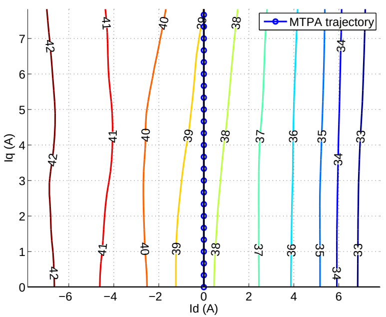
- In order to consider the effect of the iron saturation on the motor model, the mutual inductance L_M between the ring and the *d*–axis windings has been computed for different motor working point.

Map of L_M (μH) with distributed coil winding



- L_M depends mainly on the I_d current
- L_M is practically constant along the MTPA trajectory
- In all the plane the saliency variation is quite low

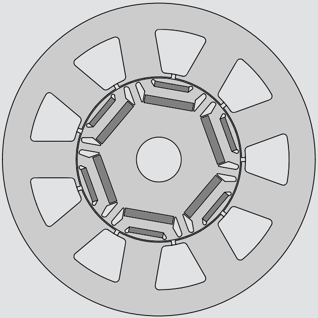
Map of L_M (μH) with concentrated coil winding



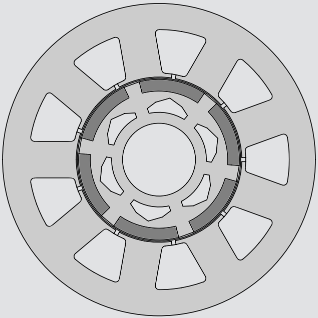
- The mutual inductance is slightly smaller than the distributed coil winding case
- Saturation does not affect mutual inductance

IPM and inset rotor configuration

IPM motor



INSET motor



Sensorless capability

Both the motors present a magnetic saliency, more precisely the small signal magnetic saliency can be computed as:

$$\xi_{\omega_h} = \frac{1 + b/f}{1 - b/f}$$

where b/f is the ratio between the amplitude of the backward and forward sequence of the current signal, given by

$$\frac{b}{f} = \frac{\sqrt{(L_d - L_q)^2 + M_{dq}^2}}{L_d + L_q}$$

where L_d and L_q are the d– and q–axis differentially inductances and M_{dq} is the dq mutual inductance due to the cross–saturation.

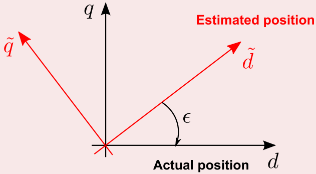
Estimation error due the cross–saturation

Effect of cross–saturation

The estimated position error due to the cross–saturation is

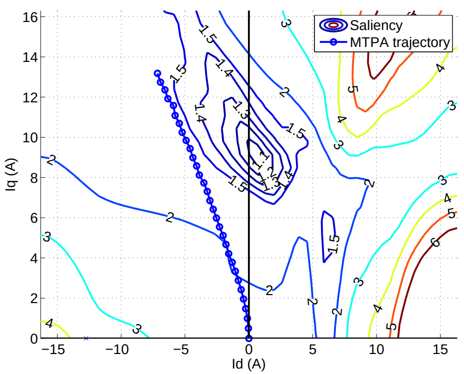
$$\epsilon = \frac{1}{2} \arctan \frac{2M_{dq}}{L_d - L_q}$$

$\Rightarrow$ a compensation algorithm is necessary to correct the position estimation error



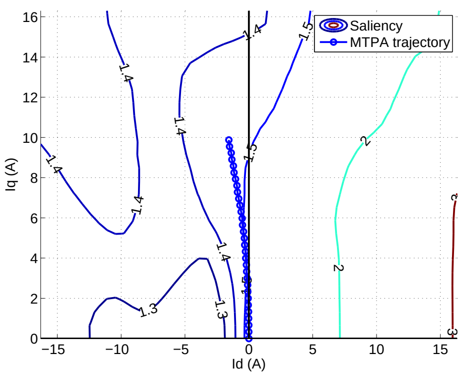
The critical point is when $M_{dq} = 0$ and $L_d = L_q$ simultaneously

Magnetic saliency ξ_{ω_h} in the $d-q$ plane, IPM motor



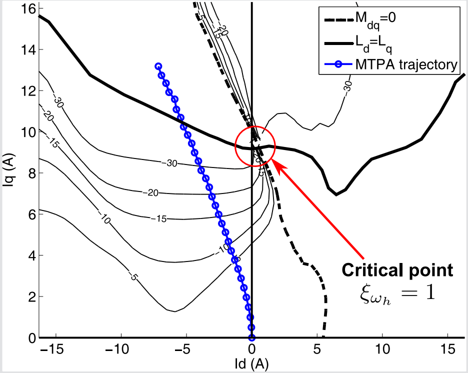
- The magnetic saliency remains high in all the left–plane $\Rightarrow$ good for control purposes

Magnetic saliency ξ_{ω_h} in the $d-q$ plane, INSET motor



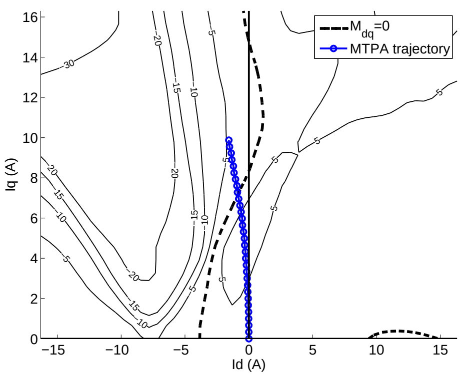
- Magnetic saliency is smaller than the IPM case, but always > 1

Estimated error in the $d - q$ plane, IPM motor



- When $L_d = L_q$ and $M_{dq} = 0 \Rightarrow \xi_{\omega_h} = 1 \Rightarrow$ the sensorless detection of the rotor position is not possible

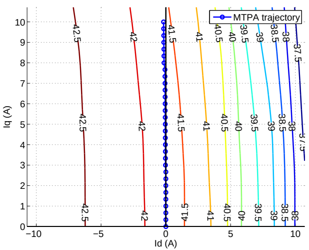
Estimated error in the $d-q$ plane, INSET motor

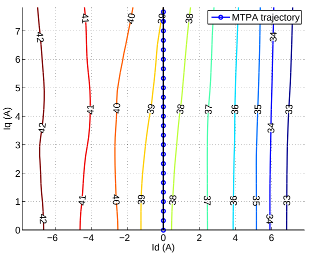


- Estimated error along the MTPA trajectory lower than the IPM $\Rightarrow$ the curve $M_{dq}=0$ close to MTPA
- The limit $L_d = L_q$ is not present since it is out of the plot limits

Estimated error in the Ringed motor

- The high–frequency saliency is guaranteed from the ring effect in all the $d - q$ plane (L_M almost constant)





- No estimated error occurs since the cross–saturation effect is negligible
- Control algorithm needs no error compensation

Conclusions

Conclusion

- Two SPM ringed pole motors with distributed and concentrated coil winding have been considered from the control point of view
- It is shown that ring around each pole represent an effective method to create a high frequency saliency, also when a fractional–slot winding is adopted
- It is shown that the effect of the eddy currents in the PMs give a useful contribution on increasing the saliency, but they are not enough to create the saliency without the ring

Conclusion

- An IPM and a INSET motor have been compared with the SPM motors
- Both the IPM and the INSET motor are suitable for the sensorless purpose, but an error compensation algorithm is necessary
- The Ringed–pole solution yields a negligible mutual coupling and then a negligible estimation error, too.

Related Papers by the Authors

- S. Bolognani, S. Calligaro, R. Petrella, and M. Tursini, "Sensorless control of ipm motors in the low-speed range and at stand-still by hf-injection and dft processing," in *IEEE International Electric Machines and Drives Conference, 2009. IEMDC '09.*, May 2009, pp. 1557 –1564.
- N. Bianchi, S. Bolognani, J.-H. Jang, and S.-K. Sul, "Advantages of inset pm machines for zero-speed sensorless position detection," *IEEE Trans. on Industry Applications*, vol. 44, no. 4, pp. 1190 –1198, 2008.

Related Papers by the Authors (cont.)

N. Bianchi, S. Bolognani, and A. Faggion, "Predicted and measured errors in estimating rotor position by signal injection for salient-pole pm synchronous motors," in *IEEE International Electric Machines and Drives Conference, 2009. IEMDC '09.*, May 2009, pp. 1565 –1572.

A. Faggion, S. Bolognani, and N. Bianchi, "Ringed-pole permanent magnet synchronous motor for position sensorless drives," in *IEEE Energy Conversion Congress and Exposition, 2009. ECCE 2009.*, 2009, pp. 3837 –3844.

Related Papers by the Authors (cont.)

A. Faggion, N. Bianchi, and S. Bolognani,
"A ringed–pole spm motor for sensorless drives – electromagnetic analysis, prototyping and tests," in *IEEE International Symposium on Industrial Electronics, ISIE 2010*, Bari, IT, Jul. 4–7, 2010.

Thank you for the attention.